A Study of the Thermal Regime of Port Moody Arm, Burrard Inlet, BC

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PREFACE

This report provides information on the heat budget of Port Moody Arm, Burrard Inlet, BC.

This study complements others that were also were initiated in response to potential increases in the thermal discharge from British Columbia Hydro and Power Authority's (BC Hydro) Burrard Generating Station, into the marine waters of Port Moody Arm. This gas-fired steam electric generating station operates under a permit from the provincial government, and utilizes a once-through seawater cooling system. The permit allows for the discharge of up to 1.7 million m^3 daily of cooling waters ($\leq$ 27 °C), drawn from, and discharged to, Port Moody Arm.

An environmental impact study to assess any effects due to the thermal discharge was a requirement of an amendment to the provincial permit. A study plan was submitted by BC Hydro to federal and provincial regulatory authorities in 1996, and it was approved in 1997. Studies were undertaken over the following 3 years and they included surveys of migrating adult and juvenile salmonids in the main tributaries to Port Moody Arm, and an examination of the potential effects of the thermal effluent on salmon behavior and survival and on planktonic organisms. Other reports document the results of these investigations.

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ABSTRACT

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Investigations were carried out to define the thermal capacity of Port Moody Arm (PMA) to cope with the heat discharged from the cooling water discharged from BC Hydro's Burrard Generating Station (BGS). This gas-fired steam electricity generating facility discharges up to 1.7 million m^3 of heated cooling water daily, at a temperature of ≤ 27 °C, into PMA. Previous studies demonstrated the large role of the natural heat exchanges between the water and the atmosphere in the overall heat budget of PMA, and predicted that the major loss of heat from PMA was due to currents and tidal flushing into the contiguous waters of Burrard Inlet. This study augments the previous work by updating the analysis with data gathered in 1998 through new measurements. An acoustic Doppler current profiler measured currents at the entrance to PMA and enabled the calculation of the heat transported into and out of the arm by currents and tides.

During summer, monthly mean water temperatures at a depth of 2 m at eastern stations are about 2 °C - 3 °C higher than those at the western entrance to the arm. Summer maximum monthly temperatures at these stations and depth are up to 5 °C - 6 °C higher. These observations reflect the mixing with the adjacent Burrard Inlet and Indian Arm to the west. The summer water temperature gradient to the east and towards the head of the arm may be ascribed largely to the distance and lessening exchange with Burrard Inlet, and the effects of the >1 km^2 mudflats. The role of the mudflats in PMA is considerable and heat from the atmosphere is accumulated on the flats while they are exposed in summer, and then it is taken up by the seawater during tidal immersion. Fourteen-day mean water temperatures measured on the mudflats (i.e., not including mud surface temperatures when the mudflats are drying) were up to 1.37 °C higher than nearby sea surface temperatures in non-mudflat areas from June to October 1997. The heat budget calculation for summer 1997 showed that the additional heat provided to PMA by the twice-daily export of the tidal prism overlying the shallows and mudflat was greatest during early August, being about 80% of the heat discharged to the arm by the BGS operating at typical summer levels. Cumulatively over the mid-June to early September 1997 period, the shallows contributed additional heat to the arm equivalent to about 25% of the heat discharged by the BGS.

Based on calculations for the month of October 1998, the dominant loss of heat was through currents and tidal action in the upper 6 m of the water column, amounting in this layer alone to about twice the quantity of heat added to the arm by the cooling water discharged by BGS. However, there was also an offsetting net heat gain by the arm during that period through currents and tides at mid-depths between 6 m and 10 m, and to a lesser extent below 10 m to the seabed. The cumulative result of the October 1998 calculation over the entire water column indicated a large overall loss of heat from PMA to Burrard Inlet by tidal action.

When the tidal heat transport component was included with the other components of the overall heat budget (i.e., atmospheric exchanges, heat storage in the water and BGS heat

discharge), the overall heat budget for the arm "balanced" to within a small residual for October 1998. These results indicated that more than 80% of the BGS thermal discharge to PMA in October 1998 left the arm due to currents and tidal exchanges with Burrard Inlet proper, while the remainder was lost to the atmosphere. It was not possible to extend the tidal heat transport calculation to the summer months (when the magnitude of the heat discharged to Burrard Inlet may be greater than that calculated for October 1998), but observational evidence indicates that water temperatures in PMA are well regulated by natural processes. In the summer, the arm starts losing heat through natural processes in late July to early August, regardless of BGS cooling water discharge levels. There is also a lack of basin-wide response to the BGS heated cooling water discharge and heat did not appear to be sequestered within the water body for longer than a tidal cycle.

While the heat budget analysis provided the most quantitative estimate of the impact of the BGS on PMA, water temperature data provide strong observational evidence of the limited impact of the BGS. The shutdown of the BGS for most of summer in 1996 provided a fortuitous opportunity to compare water temperature during that summer with those of years where normal BGS operations prevailed. This comparison between years showed that an increase in mean summer water temperatures throughout the PMA of only 1° to 2 °C may be attributed to the normal operation of the BGS, and only in the upper approximately 5 m of water. Thus, it appears that the effect on the temperature of PMA of "*El Nino*" in 1997 - 1998 was an increase in the order of 2 °C. In a "near-field" zone within 100 m of the BGS cooling water discharge, monthly mean temperatures were a few tenths of a degree higher than elsewhere in the arm, and only in the upper few meters. Water temperatures measured at half-hourly intervals in this "near-field" were up to 3 °C higher than the BGS intake cooling water temperatures during the non-summer months, and less than 1 °C during July and August. To put these values in perspective, all stations throughout PMA exhibited a daily variability of about 3 °C in summer that arose from natural atmospheric heating.

RÉSUMÉ

Taylor, A.E., D.B. Fissel, and I.K. Birtwell. 2001. A study of the thermal regime of Port Moody Arm, Burrard Inlet, BC. Can. Tech. Rep. Fish. Aquat. Sci. 2344: 128 p.

Une étude a été réalisée pour déterminer dans quelle mesure la capacité thermique du bras Port Moody permettait d'absorber les calories provenant des eaux de refroidissement déversées par la centrale électrique Burrard de BC Hydro. Cette centrale thermique, qui fonctionne au gaz naturel, peut rejeter quotidiennement dans le bras Port Moody jusqu'à 1.7 million m^3 d'eaux de refroidissement réchauffées à une température ≤ 27 °C. Des études antérieures ont mis en évidence le rôle important que jouaient les échanges de chaleur entre l'eau et l'atmosphère pour le bilan thermique global du bras et ont montré que les pertes thermiques du bras devaient être dues à des courants et à des mouvements de marée dans les eaux contiguës de l'inlet Burrard. La présente étude prolonge ces travaux et approfondit l'analyse en s'appuyant sur des données recueillies en 1998 lors de plusieurs campagnes de mesure sur le terrain. Un profileur de courant acoustique Doppler a permis de mesurer les courants à l'entrée du bras et de calculer les flux de chaleur entrant et sortant par l'intermédiaire des courants de marée.

Au cours de l'été, les moyennes mensuelles de la température de l'eau relevées à 2 m de fond dans les stations de l'est sont environ 2 °C à 3 °C plus élevées que celles enregistrées dans l'entrée ouest du bras. Les moyennes mensuelles maximums de la température enregistrées l'été aux mêmes endroits sont de 5 °C à 6 °C plus élevées que les valeurs précédentes. Ces observations mettent en évidence un mélange des eaux du bras avec celles de l'inlet Burrard et du fjord Indian Arm à l'ouest. Le gradient thermique constaté en été à l'est et vers l'entrée du bras est sans doute largement dû à la distance, à la diminution des échanges avec les eaux de l'inlet Burrard et à l'effet des slikkes (vasières) dont la superficie totale dépasse 1 km^2. Les slikkes jouent un rôle très important dans le bilan thermique du bras puisqu'au cours de l'été, la chaleur de l'atmosphère est transférée à la vase découverte à marée basse, puis à l'eau de mer lorsque la marée recouvre les bancs vaseux. Entre juin et octobre 1997, la température moyenne de l'eau enregistrée sur quatorze jours au-dessus des slikkes (excluant la température de la vase à marée basse) était de 1.37 °C supérieure à celle de l'eau voisine. Les calculs portant sur le bilan thermique pour l'été 1997 ont montré que la quantité de chaleur apportée au bras par l'exportation biquotidienne du prisme de marée au-dessus des slikkes et des hauts-fonds était maximum au cours du début du mois d'août et qu'elle représentait alors environ 80% de la quantité de chaleur déversée par la centrale thermique Burrard lorsque cette dernière fonctionnait à son niveau estival typique. Sur l'ensemble de la période allant de la mi-juin au début septembre 1997, les hauts-fonds ont apporté une quantité de chaleur équivalente à environ 25% de celle apportée par la centrale thermique Burrard.

Les calculs effectués pour le mois d'octobre 1998 montrent que la majorité des calories étaient évacuées par l'intermédiaire des courants et des marées dans la couche de 6 mètres immédiatement sous la surface, et que la quantité de chaleur exportée dans cette couche était environ deux fois plus grande que celle ajoutée au bras par le déversement des eaux de refroidissement de la centrale thermique Burrard. On a cependant également constaté qu'au cours de cette même période, les courants et les marées engendraient un bilan calorifique positif du

de cette même période, les courants et les marées engendraient un bilan calorifique positif du bras (gain de chaleur) entre 6 m et 10 m, et dans une moindre mesure entre 10 m et le fond. Globalement, les calculs effectués pour le mois d'octobre 1998 sur l'ensemble de la colonne d'eau indiquent qu'il existe un important transfert de calories du bras Port Moody vers l'inlet Burrard sous l'effet de la marée.

Lorsque la composante correspondant au transport thermique sous l'effet des marées est ajoutée aux autres composantes du bilan thermique (c.-à-d. aux échanges atmosphériques, au stockage de la chaleur dans l'eau et au déversement de calories par la centrale thermique Burrard), le bilan thermique global du bras est pratiquement nul pour le mois d'octobre 1998. Ces résultats indiquent que plus de 80% des calories déversées par la centrale thermique en octobre 1998 ont été emportées par les courants de marée vers l'inlet Burrard, tandis que le reste de ces calories ont été absorbées par l'atmosphère. Il n'a pas été possible d'étendre les calculs sur le transport thermique dû aux marées à la période estivale (lorsque la quantité de calories déversée dans l'inlet Burrard dépasse peut-être celle calculée pour le mois d'octobre 1998), mais les mesures indiquent que la température de l'eau dans le bras Port Moody est bien régulée par des processus naturels. En été, entre fin juillet et début août, le bras commence à perdre des calories par l'intermédiaire de ces processus naturels, quelle que soit la quantité d'eaux de refroidissement déversée par la centrale thermique Burrard. On a par ailleurs observé que le bassin dans son ensemble ne réagissait pas aux déversements de la centrale et que les calories apportées par ces déversements ne semblaient pas demeurer dans la masse d'eau plus longtemps qu'un cycle de marée.

L'analyse du bilan thermique a fourni une estimation quantitative de l'impact de la centrale thermique Burrard sur le bras Port Moody mais les températures de l'eau relevées indiquent clairement, à elles seules, que la centrale n'a qu'un impact thermique limité sur le bras. La fermeture de la centrale pour la quasi-totalité de la période estivale en 1996 fut l'occasion pour les chercheurs de comparer les températures de l'eau observées dans le bras avec celles mesurées au cours des étés où la centrale fonctionnait normalement. Cette comparaison a montré que le fonctionnement normal de la centrale thermique Burrard ne peut qu'engendrer une hausse de la température de l'eau comprise entre 1° et 2 °C, et que ce phénomène ne concerne que la couche supérieure dont l'épaisseur est d'environ 5 m. Il semble d'ailleurs qu'en 1997-1998, El Niño ait contribué à lui seul à augmenter la température de l'eau du bras Port Moody d'environ 2 °C. Dans la zone située dans un rayon de 100 m autour du déversoir des eaux de refroidissement de la centrale Burrard, les moyennes mensuelles de la température de l'eau dépassaient de quelques dixièmes de degrés la température de l'eau dans d'autres zones du bras mais cette différence n'a été observée que dans la couche de quelques mètres immédiatement sous la surface. Au cours des mois non estivaux, les températures de l'eau mesurées toutes les demi-heures près du déversoir de la centrale pouvaient dépasser de 3 °C la température des eaux de refroidissement puisées par la centrale mais cette différence n'était que de 1 °C en juillet et en août. Toutes les stations de mesure situées dans le bras Port Moody ont enregistré une variabilité quotidienne de la température de l'eau de l'ordre de 3 °C en été, variabilité due au réchauffement naturel de l'eau par l'atmosphère.

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INTRODUCTION

This report represents one component of a series of environmental studies concerning the real or potential effects of cooling water discharged by the Burrard Generating Station (BGS) on the receiving waters of PMA. As part of the upgrade of the operations to the BGS, in 1996 BC Hydro prepared an environmental impact study plan (BC Hydro 1996a) designed to assess effects of the cooling water discharge on water quality and biological communities in the receiving environment. This report, together with an earlier report of a related study for the preceding year (Fissel et al. 1998) addresses one of the study plan components, i.e. the thermal regime of PMA, in terms of understanding the role and effect of the BGS in relation to other thermal processes within the arm.

A number of studies (Hodgins and Webb 1991; Hodgins 1993) have been conducted previously on the thermal regime of the receiving waters of PMA in relation to the heat discharged from the BGS. A hydrodynamic model of heat dispersion within PMA was developed and used to assess the thermal effects of the BGS under a variety of BGS operating scenarios (Seaconsult 1995). Concern was expressed that the available data on which the modeling had been based might be deficient due to insufficient information regarding water temperature at various depths (including surface waters). A particular topic of potential concern was uncertainties in the thermal contribution to PMA from solar radiation and the tidally exposed mudflats towards its eastern head.

In August 1995, BC Hydro initiated an extensive program to collect data on water temperatures at several stations in PMA (Figure 2). This program was continued and it was expanded through 1998. In addition, water temperatures measured by other groups were made available to the program: 9 stations were monitored for part of 1995-1996 as a student project of Centennial High School, Coquitlam, BC (R. MacVicar, pers. comm.), and detailed temperature-depth profiles were acquired periodically at 6 stations as part of a graduate student project at the University of British Columbia (M. Henry, pers. comm.). In 1997, ASL Environmental Sciences processed and analyzed the water temperature data sets acquired from PMA up to and including the summer of 1997 (Fissel et al. 1998). The detailed analyses of these data sets were used to evaluate the accuracy of the earlier hydrodynamic modeling study (Seaconsult 1995). Moreover, the ASL study was carried out to develop an improved understanding of the thermal input originating from natural sources, such as solar radiation and heating of water on the mudflats, as distinct from the contribution of the BGS. The adequacy of the existing database was evaluated in terms of its ability to provide adequate quantitative estimations and understanding of natural thermal processes influencing the waters of PMA; and of the impact of heated cooling water discharged by the BGS on the same body of water. Recommendations made in the 1997 study (Fissel et al. 1998) were applied in conducting the 1998 thermal monitoring program for PMA, and in the subsequent data analysis reported herein.

EARLIER STUDIES OF THE THERMAL REGIME

Previous oceanographic studies of PMA are presented below but a more detailed review can be found in Fissel et al. (1998).

Physical setting and early oceanographic studies

The Burrard Generating Station (BGS) is situated on the north shore of PMA, at the eastern end of Burrard Inlet (Figure 1). The arm has a length of 6.5 km and a mean width of 0.9 km. The mean depth at low tide is 8.8 m, although much of the central portions of the arm have water depths of the order of 10 m, with water depths exceeding 20 m in the comparatively narrow entrance to the arm. The arm also includes over 1 km^2 of natural mud flats which dry at low tide. Unlike most British Columbia coastal inlets, including Indian Arm and the remainder of Burrard Inlet, PMA receives very little direct freshwater runoff as only a few small streams drain into the arm (e.g., Mossom Creek, Noons Creek, Sutterbrook Creek, Schoolhouse South Creek and Schoolhouse North Creek; Greenbank et al. 2001).

Oceanographic observations have been made in eastern Burrard Inlet on an occasional basis dating back to as early as 1931, but the first known measurements in PMA itself were made in the 1950's (Patrick 1957). The first systematic study of the oceanography of PMA was made by Waldichuk (1964). He found that the water circulation patterns within PMA and exchanges with eastern Burrard Inlet were clearly dominated by tidal flows. Because of the stronger ebb flows in eastern Burrard Inlet enhanced by estuarine circulation of the Indian Arm-Burrard Inlet system, it was "expected that the water removed on a given ebb tide from Port Moody will not likely return on the next flood, in the surface layer... there could conceivably be a return of the effluent ... on the next flood; however, it would be very highly diluted..." (Waldichuk 1964).

In the mid-1970's, an oceanographic study of the entire Burrard Inlet waterway, including Indian Arm and PMA, was carried out by Davidson (1979). The study included collection of profile data, at least once each month, for the period September 1974 to October 1975. To the best of our knowledge, no large scale oceanographic studies have been undertaken in PMA since Davidson (1979), other than those directly related to the BGS (as discussed below). A more recent program was conducted by researchers at Simon Fraser University (Laval 1997) in which the feasibility of using an Autonomous Underwater Vehicle (AUV) to map water temperatures and effluent plumes in coastal waters was tested in the vicinity of the BGS in September and October 1996.

Earlier thermal studies related to the BGS (1976-1995)

Surveys of the benthos and water quality in PMA within the vicinity of the BGS were carried out by environmental consultants in 1976 and again in 1980 (Beak 1976, 1980). The latter study included a comprehensive review of the circulation and heat balance of PMA, as well as some estimates of the BGS heat discharges in relation to natural processes, all based on historical data sets and first-order computations. Tidal velocities and flushing rates were estimated using a first-order model of the time-varying water levels due to the major (M_2) tidal constituent. The tidal

prism (the amount of water which flows into the region and leaves on ebb tide) was computed to be 12.2×10^6 m^3, which represents approximately one-third of the total volume of the arm.

Beak (1980) examined the heat budget for PMA using monthly data derived by Elliot (1965) for the southern Strait of Georgia. The summer values suggested that the order of magnitude of the maximum net heat transfer from the atmosphere to the ocean is 7.4×10^{13} J over the entire arm, each summer day. Of this total, about 27% was attributed to warming of the waters in the arm over the summer months due to atmospheric transfer (based on the quasi-monthly data of Davidson 1979). The remainder of the accumulated heat (5.4×10^{13} J each summer day) in addition to the heat received from the BGS, is apparently lost through horizontal transfer due to tidal exchanges between PMA and the remainder of Burrard Inlet. A first order estimate of heat removed from the arm each day due to tidal exchanges with eastern Burrard Inlet was computed as 6.4×10^{13} J each summer day, a value which agrees within an order of magnitude with the estimated quantity of heat received from atmospheric exchanges. Given overall numerical agreement using these very approximate first-order estimates, Beak (1980) concluded that tidal exchange was a very effective dispersion mechanism for dissipating heat from PMA.

A series of hydrodynamic studies was conducted in PMA during the early part of the 1990's (Hodgins and Webb 1991; Webb 1992; Hodgins 1993). Baseline data gathered then included hydrographic (CTD), dye tracer and current measurement surveys, in addition to thermistor time series at several stations within the arm. Based on these and operational data for BGS, the thermal effect of the BGS in the water of the arm was predicted numerically by Seaconsult (1995) using depth-averaged hydrodynamic and thermal advection/diffusion models. These models predicted that the influence of BGS on the local thermal regime outside a near-field mixing zone, is approximately 3° to 4 °C.

The Seaconsult hydrodynamic model (1995) did not explicitly resolve several of the oceanographic processes expected in the arm (e.g., baroclinic exchange, wind forces, etc.). The model predicted an average increase in surface water temperature of 1° to 2 °C over the tidal cycle in the summer, for BGS heat discharges at the maximum allowable level (i.e. 1.7×10^6 m^3 d^{-1} and a discharge temperature 27 °C). Under this worst-case scenario, the Seaconsult model predicted the area influenced by the BGS thermal discharges to be about 40% of the area of PMA. Model results, as corroborated by dye tracer studies, indicated that the BGS discharge is a strong jet directed eastward along the northern shoreline, which has a significant effect on circulation in the arm: "It causes a clockwise gyre located south and east of the outfall pipes that is not naturally present in the Arm. This circulation feature results in a cross-channel transport...over a broad area. However, the jet and resultant gyre have no net effect on the total flushing characteristics of Port Moody Arm." (Seaconsult 1995).

Although the Seasonsult (1995) model did not resolve the near-field mixing region for the BGS heated cooling water discharge, certain observations (Hodgins 1993) have indicated that the near-field thermal plume extends to the east from the BGS to a location off the loco pier. Surface temperatures ranged from 4° to 5 °C above background near the surfacing boil, to 3.5 °C above background at a distance of 500 m from the boil (Hodgins 1993, as measured on

September 16, 1993 under a total BGS discharge of 1.3×10^6 m^3 d^{-1} with an outflow temperature of 26 °C).

BGS thermal study of 1997 - 1998

The extended BC Hydro temperature data sets, as collected from August 1995 through to the summer of 1997 (Figure 1), were the basis for a detailed analysis of the thermal regime of PMA (Fissel et al. 1998). In addition to the ongoing collection of temperature data from the BC Hydro temperature monitoring program, measurements were made in the summer of 1997 to quantify the role of the extensive mudflats on the thermal regime of PMA (Fissel et al. 1998). The effect of the mudflats (and also the shallows) on the heat budget for PMA was found to be significant in terms of the summer thermal regime. Our 1997 measurements and calculations demonstrated that vertical heat exchanges with the atmosphere result in enhanced heating in summer of the shallow water, which is exported approximately twice daily from the mudflats to the main body through tidal action. A significant quantity of additional heat is released from the mudflats in this way to PMA during the peak of the summer heating season; in early August, 1997, for instance, the quantity of additional heat from the mudflats is at its maximum and is similar in magnitude to the heat discharged from the BGS when operating at typical levels (Fissel et al. 1998). Also, within the mudflats at soil depths below about 0.4 m, heat is accumulated during the warm season (July to September) and then released later over time scales of weeks to months during the cooler fall period. This mechanism arises because of the low thermal diffusivity of the seabed. The total amount of heat stored in summer and released later in the fall is small, and is less than one-tenth of the heat discharged by the BGS, or less than one-tenth of the net heat from atmospheric exchanges (Fissel et al. 1998).

The total heat budget for PMA over 14-day intervals through the summer months of 1997 (typical BGS operations) as well as during the summer of 1996 (much reduced BGS operations) was calculated. This fortuitous operational history of the BGS permitted an empirical estimate of the effect of the BGS on the waters of the arm. The heat budget computation utilized various measured data and robust empirical equations (Fissel et al. 1998). The heat content of the waters of PMA was computed with data derived from BC Hydro's extensive water temperature monitoring network. The difference in heat accumulated in the water column during the summer of 1997 versus 1996 was very small compared to the large difference in heat discharged to PMA by the BGS between these years. Computations of the atmospheric heat exchanges were made using local meteorological and oceanographic data sets, and humidity and cloud cover data from the Vancouver Airport weather station. These computations showed that the net value of the atmospheric heat exchanges for the summertime represents a major heat input to the arm; the magnitude of this heat input was similar for 1996 and 1997.

The balance of these heat budget terms (i.e., net atmospheric heat plus BGS heat, less the increase in heat stored in the water column) indicates that 90% or more of the total heat received by the arm during the warm summer season is quickly lost from the system, presumably by tidal exchange through the westernmost portions of PMA with the cooler and deeper waters of Burrard Inlet and Indian Arm (Fissel et al. 1998). These heat budget results indicate that tidal

exchanges are effective and important in removing excess heat discharged by the BGS to the arm.

The results of the previous numerical hydrodynamic model (Seaconsult 1995) which predicted the level of heat dispersed into PMA from BGS, were evaluated by means of analyses of water temperature data and some diagnostic modelling. Seaconsult combined vertical heat losses via atmospheric exchanges and to deeper water into a single vertical heat exchange coefficient; this formulation did not agree well with careful first-order estimates of these vertical thermal processes (Fissel et al. 1998). Considering the predicted average temperature increase due to the BGS cooling water discharge in the Seaconsult model scenarios, we estimated that their vertical heat exchange coefficient implied a rate of cooling which was much larger than can be justified when considering the actual magnitudes of the losses via vertical atmospheric heat exchanges and to deeper water.

The previous hydrodynamic modelling by Seaconsult (1995) indicated that tidal exchange provides a weak heat loss process, in distinct contrast and contrary to the high heat loss attributed to tidal exchange by the heat budget computations. There are a number of possible reasons that might account for the differences between this earlier numerical model and observations now made possible by the extensive data sets (Fissel et al. 1998). To improve on the model predictions, we considered that it may be necessary to change model parameters, expand the model domain to include more of Burrard Inlet, or change the numerical modelling approach from the present depth-averaged model. The latter change could be required if, for example, depth-varying processes proved more important than previously thought. More information involving additional data collection, particularly in the western and central portions of PMA, would be required to resolve the issues of how to improve the numerical modelling output (Fissel et al. 1998).

As part of our 1997 determinations, we recommended that further refinements of the heat budget computations for PMA should be carried out either as an alternative to, or complementary to, the development of an improved numerical model. Based on the existing data sets collected from 1995 to 1997, it was demonstrated (Fissel et al. 1998) that heat budget analyses can attain a reasonable degree of accuracy for determining the thermal processes of PMA. Accordingly, we concluded that extending the heat budget approach, in conjunction with a proposed modest expansion of the network of field measurements, would lead to improved accuracies in computing the important heat sources and sinks within PMA. The heat budget computation would also be useful for quantifying the thermal effect on PMA of changes in the major heat sources, including changes in the heat discharged by the BGS.

An evaluation of the 1995 to 1997 data sets was carried out before their use in the present study. Fissel et al. (1998) made recommendations for improvements to the existing data collection network which consisted of:

1. Obtaining continuous measurements of ocean current profiles, over at least one month, in the narrows at the entrance to the PMA, and obtaining more water temperature data in the same

area, in order to provide improved quantitative values of the heat lost from the arm by tidal exchange.

2. Changing the vertical sampling scheme at the existing water temperature monitoring stations to provide measurements at greater depths and to enable more accurate determinations of the total heat content of the water column.

3. Monitoring mudflat temperatures in the spring and summer for one more year, at another mudflat in the arm closer to the BGS.

4. Adding one temperature monitoring station at the end of the large containment boom just east of the BGS discharge outlets, to better define the near-field area of the thermal plume.

5. Encouraging the Greater Vancouver Regional District (GVRD) to operate a humidity sensor at its Rocky Point weather station, as this would further reduce uncertainties in computing the net atmospheric heat exchanges through better estimation of the latent heat flux term.

1998 STUDY OBJECTIVES

The present study represents a continuation of the previous data analyses (Fissel et al. 1998) applied to BC Hydro's network of water temperature monitoring data throughout PMA, including an additional year of temperature measurements during 1998.

The overall goal of the present study was to develop an improved understanding of the thermal regime for PMA, and thus provide useful inputs to other environmental studies concerned with the potential effects of the operation of BGS on sensitive species and life stages of aquatic life therein.

The specific objectives of this study, which follow in large part the recommendations of the previous study (Fissel et al. 1998) were to:

extend BC Hydro's temperature database and analytical results to include another year, including a third complete summer;
improve the temperature monitoring program, based on the analyses and evaluation of the 1995-1997 data sets (Fissel et. al. 1998). This would be done through:
-improved horizontal resolution of the temperature network, by increasing the number of stations in the western arm (see objective below), with a corresponding decrease in the number of stations in the eastern arm, and
-improved vertical resolution of the network by reducing the number of thermistors in the upper two meters of the water column in favor of more thermistors at greater water depths;
determine the amount of heat exchanged between PMA and Burrard Inlet proper, in relation to the total heat budget for the arm, by:
-establishing one or two additional water temperature stations in the western portion of the arm while continuing to monitor at Gosse Point, and

-undertaking continuous measurements of ocean current profiles over a one month period near Gosse Point in 1998; the realization of this objective would allow, for the first time, direct computation of the effective tidal exchange and hence the horizontal heat exchanges;

further improve an understanding of the role of the mudflats on the thermal regime by the operation of temperature loggers on the seabed at the mudflats off Dockrill Point and at the eastern mudflats (at Station MF); and

improve understandings of the near-field area of the BGS thermal plume, through the addition of one temperature monitoring station at the end of the large containment boom just east of the BGS discharge.

In the course of the data analyses carried out for this study, the analytical techniques used were designed and implemented in order to distinguish temperature effects attributable the BGS discharge from those due to natural sources, to the extent possible.

METHODS

The collecting of data used in the previous year's report (Fissel et al. 1998) was continued for 1998. However, following recommendations included in that report, significant modifications were made to the data collection program at the end of 1997 and in early 1998. This section describes the procedures employed and data sets collected in 1998.

WATER TEMPERATURE DATA SETS

Since the summer of 1995, BC Hydro has been managing a network of stations for measuring seawater temperatures in the vicinity of the BGS cooling water intakes and discharge points, and around the periphery of PMA (Figure 2). Each station consists of a sensor chain of several miniature temperature loggers spaced at intervals from near the surface to the available depth (Table 1). The sensor chains are tied off on floating structures (docks, etc.) so that temperatures are recorded at constant depths from the sea surface throughout the tidal cycle. The distance of each station from the shoreline varies from 30 m to 175 m (Table 2). A full description of this network and the temperature loggers is contained in Fissel et al. (1998). By 1998, temperature data were being logged half-hourly at up to 14 stations, encompassing depths from 0.5 m to 12 m; in all, some 46 loggers were deployed.

Water temperature stations: modifications for 1998

The report on the thermal regime of PMA by Fissel et al. (1998) made a number of recommendations that would improve the temperature monitoring network, with respect to future analytical needs (Fissel et al. 1998). Most of these recommendations were implemented by spring, 1998. Figure 2 shows the locations of the 1998 stations for measuring water temperatures on the hydrographic chart of PMA. Table 1 is a graphic representation of sensor depth distribution at each station. Table 2 gives station names and further details. An examination of

the station-location map and tables from last year's report (see Figure 1 and Table 3.1, in Fissel et al. 1998) shows the following changes that were effected for 1998:

- Temperature loggers at 0.1 m and 1.0 m depth were decommissioned [Fissel et al. (1998) recommended that the depth distribution was unnecessarily weighted to the near-surface and improved measurement capacity was needed in the 3 m to 8 m region].

- Additional loggers were placed at 3.5 m depth at all stations (March 1998) [as above].

- Station IN (Ioco Net Pens) was decommissioned [Fissel et al. (1998) noted IN contributed little beyond that of Station ES, which is located some 0.6 km to the west].

- Station BO (Burrard Outfalls) was deployed on the containment boom, some 70 m from the BGS discharge point (March 1998) [Fissel et al. (1998) had made a recommendation for a "near-field" station in this area].

- Station RW (Reed Point West) was deployed to measure temperatures at greater depths than available at PE.

- Station MM (Mossom Mudflats) was deployed on the tidal flats near the entrance to Mossom Creek, recognizing the importance of water temperatures within the mudflat ecology.

- An acoustic Doppler current profiler (ADCP) was deployed in the narrow entrance to PMA for the month of October 1998. Temperature measurement Stations AD and GC were part of the ADCP installation.

- Stations GW and GE were deployed for the month of October 1998, some 70 m from shore and east and west of the ADCP, to facilitate a detailed currents/heat budget analysis.

UBC water temperature and salinity profiles

The University of British Columbia started taking water temperature and salinity profiles at occasional intervals in PMA during the summer and fall of 1998. These were made available to this project by M. Henry (University of British Columbia, Vancouver, BC, pers. comm.). The locations of the six UBC stations are shown on Figure 2 and consist of water temperature and salinity data at 1-metre increments to the seabed.

Mudflat surface and water temperature measurements

Technical difficulties limited a continuation and modest expansion of the mudflats temperature measuring program beyond 1997. Mudflat Station MF was reoccupied, but surface and water temperature measurements were obtained only from mid-June to early July 1998. A new station was installed in June 1998 off Dockrill Point at the mouth of Mossom Creek (Station MM, Figure 2), and data were acquired only from mid-June to the end of August (Appendix H.1; Taylor et al. 1999).

Data processing, quality control and editing of the water temperature data

All data from BC Hydro temperature loggers which were downloaded subsequent to fall 1997 were supplied to ASL Environmental Sciences as binary files directly from the Stowaway™ loggers (downloads were made in January, March, May, June, July, September, October and November 1998). ASL processed the data in a fashion similar to that developed in 1997 (Fissel et al. 1998).

Time base: All data are based on Pacific Standard Time expressed as an ongoing Julian day index, defined such that 1995 01 01 00:00 = Day 1.000. Note that this definition may differ from other implementations of Julian dates [e.g., astronomical definition, (Press et al. 1989)]. Table 3 gives the first day of each month and the equivalent Julian day relative to our definition for this project.

Water temperature statistics

An extensive computation of water temperature statistics was undertaken for this report, using the entire data set that had been collected since 1995.

14-day: Mean, standard deviation, maximum and minimum values of water temperatures were calculated on a 14-day interval basis for the entire data set. This interval was used mainly in the heat budget/atmospheric exchange analysis to provide additional detail than obtainable from monthly data.

Monthly: Mean, standard deviation, maximum and minimum values of water temperatures were calculated on a monthly basis for the entire data set.

Seasonal: The differences of monthly mean, maximum and minimum temperatures at various stations from those at Station GP (Gosse Point) at the western entrance to the arm were calculated for a depth of 2 m for the period 1995-1998. These differences were used to highlight seasonal variations. The data used were from Appendix G.1 (Taylor et al. 1999).

Multi-year statistics: A brief investigation was carried out of long-term, historical water temperature data for other areas of BC. In particular, a 9-year data set of monthly mean sea surface temperatures and long-term monthly "normals" were obtained for two lighthouses: Entrance Island in the Strait of Georgia, and Amphitrite Point, on the west coast of Vancouver Island, BC. The data were used for evidence of *El Nino* and were obtained from Fisheries and Oceans, Canada.

Temperature contour maps and longitudinal transect sections

Contour maps of monthly mean water temperatures at depths of 0.5 m, 2 m and 5 m were made using the monthly statistics, for February to September 1998. There were fewer BC Hydro monthly mean data for October (Taylor et al. 1999) and only a single UBC temperature profile on October 29; hence, a contour map for the month of October was not attempted. Instead, a

contour map was made for around noon-hour on October 29, 1998, using the UBC water temperature profiles and the BC Hydro stations' half-hourly data for this date and time.

Contouring has been undertaken with this limited data to highlight some general trends. Note that the contour interval is the same as the digital resolution of the temperature sensors (see Taylor et al. 1999). UBC data have been included where possible [refer to Taylor et al. (1999) concerning the accommodation of such "non-monthly" data in a "monthly mean" plot].

Longitudinal transect sections of monthly mean water temperature versus depth were made for June to September, and for noon-hour temperatures on October 29, 1998. The transect chosen attempted to include most of the stations, including the UBC profiling stations. [Further information on preparation of these temperature-contour sections is provided in Appendix E.2 (Taylor et al. 1999)].

ADCP CURRENT MEASUREMENTS

An Acoustic Doppler Current Profiler (ADCP) instrument was operated in western PMA station (Figure 2) from September 29 to October 28, 1998. A schematic of the installation is shown in Figure 4. This unit, an ADCP "Workhorse series *Sentinel*", was manufactured by RD Instruments of San Diego, California. The ADCP technology is widely used for oceanic environmental monitoring applications (Taylor et al. 1999). Mounted near the sea bottom, the ADCP unit provides precise measurements of ocean currents (both the horizontal and vertical components) at many levels within the water column, from near-surface to near-bottom. The ADCP instrument measures velocity by detecting the Doppler shift in acoustic frequency, arising from water current (or ice) movements, of the backscattered returns of upward (20° from vertical) transmitted acoustic pulses. The Doppler shift of the 300 kHz acoustic signal is used to determine water velocities at a vertical spacing of 1 m (1-m bins). The sampling scheme involved 10-minute ensembles, composed of an average of 150 water-column pings, which results in an accuracy of $\pm$ 1 cm s^{-1} for ocean current measurements. The measurements were stored internally on a flash EPROM memory card. Data storage required about 3.6 MB of the 10 MB capacity.

The ADCP instrument, along with an acoustic release recovery device connected to the ADCP through a 65-m groundline, were deployed from the vessel MV *Fin-Power*. The instrument and mooring equipment were recovered on October 29 1998, using the vessel MV *Queen's Reach*. The ADCP was sited in a mean water depth of 30 m about 125 m NNE of the General Chemical Canada plant and 275 m SSW of Carraholly Point (Figures 2 and 3). This provided measurements of water currents over 1-m bins at depths from 2 m above the seabed upwards to within 2 m of the water surface. The instrument also measured the tilt angles and directional orientation of the sensor head.

Temperature stations deployed nearby the ADCP

The ADCP unit contains a temperature sensor inside its pressure case (denoted station AD, Figures 2 and 3). For the period of deployment of the ADCP instrument, in order to fully enable

the calculation of the heat transport due to the currents and tides at this location, BC Hydro installed water temperature stations GW and GE a few tens of meters west and east of the ADCP location, respectively (Figure 3). These stations provided water temperatures at depths of 5 m, 8 m, 12 m and 15 m from the water surface (Tables 1 and 2). Two more Stowaway™ temperature loggers were provided by BC Hydro and attached to a subsurface float anchored to the seabed (Station GC). This station provided water temperature data at equivalent depths from water surface of approximately 15 and 20 m (+/- tidal range of 2 m).

PREDICTIONS OF TIDAL WATER LEVEL

Tidal height predictions for PMA are made routinely by the Canadian Hydrographic Service (CHS) of Fisheries and Oceans Canada. More accurate tidal height predictions were made for this study from January 1, 1995 to November 30, 1998, based on tidal analysis constituent values available from CHS, instrumental measurements undertaken as part of the 1997 study (Fissel et al. 1998) and standard tidal prediction software (Foreman 1977). Summary plots of these predicted hourly water levels for PMA are found in Taylor et al. 1999.

PREDICTIONS OF TIDAL CURRENTS

The current measurement taken in the entrance to PMA in October, 1998 enabled currents to be predicted at this location for other times, using standard software (Foreman 1977). The hourly east component of the water velocity was computed for April 1, 1998 to October 31, 1998 (Taylor et al. 1999).

ROCKY POINT METEOROLOGICAL DATA

Meteorological data to support computation of the air-sea heat exchanges were obtained from the Greater Vancouver Regional District (GVRD), which operates a weather station (T9) at the tidewater park located a few meters above sea level at Rocky Point near the head of PMA (Figure 2; Fissel et al. 1998). The sensors are mounted on top of a trailer about 4 to 5 m above ground level. Measurements are made at hourly intervals. The measurement parameters used for this study were: air temperatures (°C); pyranometer measurements of incident solar radiation, [using LI-200SA sensor covering spectral range 0.4-1.1 nm, peak at 0.9 nm (W/m^2); (Fissel et al. 1998)]; wind direction (degrees from north); and, wind speed vector average (km/h).

Meteorological statistics, Rocky Point

Monthly and 14-day statistics, consisting of mean, standard deviation, maximum and minimum, were calculated for the period May 1995 to October 1998 for each meteorological parameter.

VANCOUVER AIRPORT METEOROLOGICAL DATA

Several parameters not available at the Rocky Point weather station were obtained from the Atmospheric Environment Service (AES) weather station at Vancouver Airport. These

parameters were: wet and dry bulb temperatures (°C); cloud opacity (fraction of sky obscured by cloud cover, tenths); and, winds (km/h).

The published monthly summaries for the standard meteorological values at the Vancouver International Airport were also obtained.

Meteorological statistics, Vancouver Airport

Monthly and 14-day statistics, consisting of mean, standard deviation, maximum and minimum, were calculated for the period May 1995 to October 1998 for each meteorological parameter.

BGS OPERATIONAL DATA

Over the summer and fall of 1998, the BGS operated at power levels up to ~575 MW, or about 60% of its capacity. BC Hydro supplied the following key operational statistics to the project: daily heat discharged (GJ/day), a calculation of the estimated quantity of heat energy discharged daily via cooling water, to PMA; cooling water discharge temperature, daily average (°C), measured within the discharge tubes. These data reflect the temperature of the water discharged into PMA. BC Hydro also supplied "BGS unit control log sheets" for the months of July and August, 1998. These tabulate a variety of parameters at 4-hour intervals, but only the load (MW) and cooling water outlet temperatures were of interest to the project.

DATABASE DESCRIPTION

Data acquired since the report by Fissel et al. (1998) were added to the earlier data and archived in a simple ASCII file format. This ensured ease of use of the data and importation into various analytical programs, plotting routines and spreadsheets. An archive was constructed to hold all the files, in uncompressed format, on a single CD-ROM disk.

Time

The basic parameter for this database is time. Pacific Standard Time (PST) is used throughout. For convenience of this project, time was cast into ongoing Julian days (and decimal fractions), with 1995 01 01 00:00 PST = Day 1.000 PST. Refer to Table 3 for the conversion of Julian day to the first day of each month.

Parameters

The SI system of units is used throughout (the exception is some parameters used in the calculation of solar radiation). In general, error estimates are not included in the digital database (refer to Fissel et al. 1998).

Errors

Two sources of database error were evident in this project. First, there were errors associated with the instruments used to take the measurements of parameters used. Second, there were errors from the use of various formulae, many of which were empirical and did not fit perfectly to the situation in which they were applied.

Instrument errors

Stowaway™ temperature loggers:

Time: drift, up to 1 hour/year (manufacturer's estimate). As each deployment was for about 3 - 4 months duration due to logger memory limitations, a potential error of 15 minutes in time may have occurred due to drift.

A far greater source of timing error likely arose from inattention to correctness of computer clocks used to set the loggers (and the Stowaway™ Optic Shuttle) each time loggers were downloaded and reset. Field notes are not available prior to spring, 1997, but subsequent notes suggest that time corrections of minutes to (occasionally) several hours are required (1995-1997), due to inaccurate computer clocks (and the clock in the Optic Shuttle). These corrections were undertaken when known. For the 1998 data, such corrections were not necessary.

Temperature: +/- 0.1 °C over temperature range encountered in PMA waters (manufacturer's estimate; Fissel et al. 1998).

Meteorological parameters:

Accuracy is assumed to be limited to the number of digits provided by the agency (AES, GVRD); temperature: 0.1 °C; winds: 1 km/hr; wind direction: 10^{0}.

Short-wave Radiation: (manufacturer's specifications, typically 3%, 400 - 1100 nm wavelength; see Fissel et al. 1998).

The above instrument errors were acceptable for the purposes of this study.

ADCP logger: +/- 1 cm/s (see also Appendix D).

RESULTS

The edited data are presented in the Appendices of the report by Taylor et al. (1999).

EDITED DATA SETS

Water temperatures

Detailed monthly plots of the edited half-hourly water temperature around PMA gathered by BC Hydro are given in Taylor et al. (1999), for September 1997 to mid-November 1998. Prior data (since mid-August 1995) are in Fissel et al. (1998).

Figure 5 is an example of the full half-hourly data set at Station RP, Reed Point. In this plot, and those in Appendix H.1 (Taylor et al. 1999) the daily variability in the water temperatures is seen to be greatest in the summer and at depths above 8 m. The range of this variability over the span of a day or a few days is of the order of 6 °C. Daily variability in winter and at depths close to the seabed is considerably less.

Profiles of water temperature and salinity were obtained by the University of British Columbia several times a month starting in summer 1998 (locations UBC-x in Figure 2). These profiles are particularly complementary to the program by virtue of their locations along the centerline of the arm, and the detail provided at 1-m spacing. Generally, they confirm that the BC Hydro stations, located around the periphery some 30 - 175 m from the shoreline, track water temperatures elsewhere in the arm. Figure 11 (5^{th} plot from the top) shows the general similarity between water temperatures measured at Stations ES and UBC-C, some 300 m south in the center of the arm. Station UBC-R provided some data on the temperatures west of the entrance to PMA in Burrard Inlet proper, and reaffirm our earlier assumption that Station GP reflects water temperatures in this larger body of water. The UBC data are described further in Taylor et al. (1999).

Meteorological data

Air temperatures, wind speed and direction and incident solar radiation data from the GVRD weather station at Rocky Point at the eastern end of PMA (Figure 2) for October 1997 to October 1998 are plotted in Taylor et al. (1999). Prior years' data are found in Fissel et al. (1998).

Dry and wet bulb air temperatures, wind speed and cloud opacity from the AES weather station at Vancouver International Airport for May 1996 to November 1998 are provided by Taylor et al. (1999).

BGS operational data

Daily cooling water discharge temperatures and daily values of heat discharged to PMA for late-1997 and 1998 are in Taylor et al. (1999); prior years' data are in Fissel et al. (1998).

Water currents

Various plots of the east-west component (along channel) of the water currents for the month of October 1998 are presented in Taylor et al. (1999).

The current measurements taken in the entrance channel to PMA during October, 1998 enabled currents to be predicted at this location for other times, using standard software (Foreman 1977). The hourly east component of the water velocity was computed for April 1, 1998 to October 31, 1998 (Taylor et al. 1999), for the possible use in calculating heat transport over the summer. To check the prediction, we compared the currents predicted in this way for October, 1998 with the measured data for this period, and found that the agreement was excellent (Taylor et al. 1999). However, currents predicted for the preceding summer, or for periods other than October, 1998 will be prone to larger uncertainties because of unknown seasonal effects in this estuarine environment. This topic is discussed in more detail later.

STATISTICS

14-day: Mean, standard deviation, maximum and minimum values of water temperatures are tabulated in Taylor et al. (1999). See also Fissel et al. (1998).

Monthly: Mean, standard deviation, maximum and minimum values of water temperatures for all stations are tabulated in detail in Taylor et al. (1999). Monthly mean temperatures are tabulated in a more compact format and ordered by sensor depth in Taylor et al. (1999).

Meteorological: Mean, standard deviation, maximum and minimum values of GVRD Rocky Point and AES Vancouver Airport data are tabulated in monthly statistics and in 14-day statistics (Taylor et al. 1999).

CONTOUR PLOTS OF WATER TEMPERATURE DATA

Maps of 1998 water temperature contours, Port Moody Arm

Contour maps of monthly mean water temperatures are presented in Appendix A. The number and distribution of the water temperature measurement stations is limited, and caution should be exercised in use of these graphs. For instance, temperature contours in the far eastern arm in the area of the mudflat were extrapolated, since no or insufficient data were available at Station MF. Also, some anomalies appear around some UBC stations (e.g. August) but these may be simply a reflection of the method used to integrate such occasional data into the monthly plot, or due to the limited temperature resolution of the sensors.

The set of contour maps for February to October 1998 shows that, on a monthly mean basis, the following observations may be made regarding the depth and areal variation of PMA water temperatures:

- there was greater temperature variability at depths of 0.5 m and 2 m than at 5 m.

- winter and spring (e.g., February-March) surface temperatures were lower than those at greater depth, while summer surface temperatures were higher than deeper temperatures.

- monthly mean temperatures in winter and spring in the eastern arm were less than 1 °C higher than temperatures at the entrance to the arm at Burrard Inlet (see February and March contour plots).

- starting in late spring and early summer, monthly mean water temperatures increased in the eastern arm relative to those at the entrance adjacent to Burrard Inlet, creating a temperature gradient that extended the length of the arm. The result is mean monthly summer temperatures that reach 3 °C higher in the eastern arm than those at the entrance and in eastern Burrard Inlet.

- this temperature structure is typical of estuaries [Perkins (1974) noted that water temperatures in some estuaries are typically higher in summer, and cooler in winter, partly because of the shallow water and enhanced heat exchange with the mudflats].

Depth sections of 1998 water temperature contours along the length of Port Moody Arm

Contour plots of a longitudinal section running the length of PMA are presented in Appendix B. These plots use available temperature data over all depths and hence contours are far better controlled than on the contour maps, above. However, caution is advised in interpretation. The bottom topography shown on the cross-section reflects the transect's path, which is mostly along the shoreline, but which traverses mid-channel at the UBC stations.

The set of longitudinal water temperature contour maps for February to October 1998 shows that, on a monthly mean basis, there was greater temperature variability in the upper 5 m than at greater depths and below a depth of 8 m, there was little variation in temperature over the winter, spring and summer.

BGS discharge is at a depth of approximately 2.5 m below mean water surface and is directed eastwards (BC Hydro 1996b). The thermal plume is visible only in the upper few meters.

SEASONALITY IN THE WATER TEMPERATURES

Seasonality (based on monthly means)

Figure 6 summarizes the differences at depths of 2 m of monthly mean, maximum and minimum temperatures at various stations in the eastern part of PMA from those at Station GP (Gosse Point) at the western entrance to the arm adjacent to Burrard Inlet proper. The graph covers the period 1995-1998 (data from Taylor et al. 1999). This shows, for water depths of 2 m, that:

- monthly mean surface water temperatures in summer and fall were 2.5 °C to 4 °C higher at all stations in the eastern arm than temperatures in the entrance to the arm adjacent to Burrard Inlet proper.
- monthly mean surface water temperatures in mid-winter were similar or up to 1 °C higher throughout the arm to those at the entrance.
- the maximum difference between surface water temperatures in the eastern arm and at the entrance was variable and tended to occur in winter and early spring.
- the minimum difference between surface water temperatures in the eastern arm and at the entrance was variable and tended to occur in summer.

Figure 7 summarizes the year-to-year trends for near-surface (2 m) water temperatures over the summer months, as computed from the BC Hydro data sets for the 1995-1998 period. These data indicate that, at depths of 2 m:

- July: mean monthly surface water temperatures in the eastern part of the arm increased by ~ 1.5 °C - 2 °C, and in the entrance by ~ 1 °C (at GP), from 1996 to 1998.
- August: mean monthly surface water temperatures in the eastern part of the arm increased by ~ 2 °C - 3 °C, and in the entrance by 1 °C (at GP), from 1996 to 1998.
- September mean monthly surface water temperatures in the eastern part of the arm increased by 2 °C - 3 °C, from 1996 to 1998; temperatures in 1995 were higher than those of 1996 and 1997 and nearly as large as those of 1998.

Seasonality (based on 14-day means)

Figures 8a and b illustrate the variation of water temperatures with depth and season for chosen station pairs. These figures, similar to Figures 3.5a, b in Fissel et al. (1998) with the 1998 data added, are based on 14-day mean temperatures (Taylor et al. 1999). They reveal that the greatest temperature variability occurs between the surface and depths of 5 m to 8 m; during the mid- to late-winter period, the water column was nearly isothermal in 1995-1996 and 1996-1997, but less isothermal in 1997-1998, and (the lower plots of each figure) that winter 1997-1998 and summer-fall 1998 water temperatures were about 2 °C higher at depths below a surface layer, than in the previous year (*El Nino* effect?).

INTER-ANNUAL VARIABILITY IN THE WATER TEMPERATURES

The higher winter temperatures in PMA during the winter of 1997-1998 and most of 1998 are consistent with elevated sea surface temperatures observed during this period along the British Columbia Coast and the Strait of Georgia (Figure 9). The warmer temperatures have been widely attributed to the effects of *El Nino* conditions, which developed in the equatorial Pacific Ocean in the spring and summer of 1997, and continued with some interruptions through until the spring of 1998. The effects of this intense *El Nino* were evident on the Pacific Coast of British Columbia during the summer of 1997, and in inland waters by the fall of 1997. As shown in Figure 9, sea surface temperatures exceeded long-term monthly "normals" through to the spring of 1998 on the outer coast (up to 2 °C higher at Amphitrite Point) and possibly through the summer of 1998 at the inshore station at Entrance Island.

EVIDENCE IN WATER TEMPERATURES OF THE THERMAL DISCHARGE FROM THE BGS

Under normal operational levels of the BGS, the quantity of heat discharged via cooling water is substantial. That water temperatures do not rise appreciably with the BGS operation is the simplest evidence that seawater temperatures in the arm are very well regulated by losses of heat due to natural processes.

The quantification of this natural regulation of the temperature is accomplished through a calculation of the heat budget for the arm. Here we examine some of the simple observational evidence of the impact of the BGS thermal discharge on the water temperatures. An investigation of the thermal effects in the immediate vicinity of the BGS, the "near-field", follows later.

Late summer water temperatures and BGS operating levels

Water temperatures in late August-early September may be considered a surrogate of the cumulative effect of natural summer heating, natural losses and the heat discharged by the BGS to PMA. The principal feature of BGS operational levels over the four summers 1995-1998 (Figure 10, center plots) was the shutdown of the BGS for most of summer 1996. This is a fortuitous opportunity to look for a simple correlation of this variability in BGS heat discharged with water temperatures.

Figure 10 focuses on the September water temperature data and compares it to the operation of the BGS, on a 14-day means basis. Temperatures at Station GP (Gosse Point, at the western entrance to PMA) were considered representative of regional temperatures in Burrard Inlet and to be remote from the influence of the BGS. They were used as a reference to water temperatures measured within the eastern arm. September temperatures at GP were similar in 1995 and 1996, were unavailable in 1997 and increased by about 1 °C in 1998. It is likely that this is attributed to *El Nino*. The spread between September temperatures at GP and PE (Petro Canada 0.9 km southwest of the BGS) decreased about 1 °C - 2 °C between 1995 and 1996, a small change considering the large decrease in BGS heat discharged due to shutdown. Temperatures at PE increased in 1997 to about 1995 levels, as the BGS heat discharge resumed. Finally, the spread between GP and PE increased to about 3 °C in 1998. The increase of about 2 °C between PE (1997) and PE (1998) does not seem consistent with the modest increase in BGS discharge between these two years.

Looking at the plots on the right side of Figure 10, temperatures at Station BT (BGS) are representative of intake water to the BGS cooling cycle. Station ES is ~ 350 m downstream from the BGS discharge. Considering the spread between September 14-day mean temperatures at BT and ES, temperatures downstream were up to 1 °C lower than those at BT when the BGS was shut down in 1996 (right side of Figure 10), and up to 1 °C higher than those at BT during normal BGS operations.

By comparing late summer water temperatures under normal BGS operation to water temperatures when the BGS was shutdown suggests that the effect of the BGS on September mean water temperatures was of the order of 1 °C to 2 °C.

NEAR-FIELD OF THE BURRARD GENERATING STATION THERMAL PLUME

A continuing interest is to identify a more directly observable impact of the BGS on the water temperatures of PMA. Three techniques were attempted by Fissel et al. (1998) to relate BGS operational data to direct variations in water temperatures. These met with little success, largely due to a lack of BGS data on a frequency approaching the water temperature data set, and due to the absence of water temperature stations in the "near field", i.e., within a few tens of meters, of the BGS discharge plume (Fissel et al. 1998). These two shortcomings were rectified to some extent by the deployment of Station BO off the containment boom, approximately 70 m downstream of the BGS discharge (for location, see Figure F 2.4; Taylor et al. 1999); and with the availability in 1998 of BGS operational data at 4-hour intervals. While this latter interval is still eight times the interval of the temperature data, operational measurements were not taken more frequently at the BGS. For the data analysis, signals in the recordings of water temperatures were sought that could be attributed conceptually to heat discharged to PMA via BGS cooling water, and a cross-correlation analysis was undertaken on a portion of the available data in a simple attempt to identify events in nearby water temperature time-series that were correlated with variations in the BGS output; this analysis is summarized here with details provided in Taylor et al. (1999).

Evidence for the Burrard Generating Station thermal plume in the water temperatures

The contour maps of monthly mean water temperatures (Appendix A) graphically show the elevation of water temperatures in the vicinity of and east of the BGS, particularly in non-summer months when ambient water temperatures were low compared to BGS cooling water discharge temperatures. Note the clustering of higher temperature contours around Stations BT, BO and ES, particularly on the October 29 plot. The longitudinal transect sections (Appendix B) show the depth character of the BGS discharge plume. The cooling water discharge is located at a depth of approximately 2.5 m below mean water surface and is directed eastwards (BC Hydro 1996b); the thermal plume was detected only in the upper few meters of these sections within the immediate vicinity of and east of the discharge. The BGS cooling water temperatures and daily heat discharged were fairly uniform over the period covered by these transect sections (Taylor et al. 1999).

Figure 11 illustrates the overall context of water and air temperatures in PMA, and of BGS operational data, for summer and fall 1998. The maximum BGS output during this period was about 575 MW, or about 60% of BGS design capacity. Temperatures from the infrequent UBC measurements are shown for UBC-C with Station ES, affirming that the BC Hydro stations track mid-arm temperatures fairly well. Figure 12 shows nearby stations in more detail and particularly, temperature differences between these stations and BT, a station representative of water temperatures near the cooling water intakes to the BGS.

Considerable variability occurred in daily average temperatures of the BGS's cooling water discharge, and in the calculated heat released daily to PMA over the summer (upper two plots in Figure 11). Index lines A, B and C mark major reduced power events in the operational data for which we sought correlation in the water temperatures of PMA.

In early July, BGS cooling water temperatures and heat discharge are relatively low at this time [however, note the (unfortunate) coincidence of cool and cloudy weather (lower two panels, Figure 11) with the BGS output reduction that makes correlation with water temperatures ambiguous]. There is no obvious downward trend in water temperatures immediately downstream of the BGS discharge at BO, nor at ES or RP, that might be attributed to the lower operational levels. The subsequent small rise in water temperatures at BO cannot be clearly related to the increase in BGS cooling water temperatures and heat discharged, as both air temperatures and short-wave radiation increase at that time, as do water temperatures at other stations.

In late July similar comments apply as were made for early July. Also, BGS discharge temperatures appeared inconsistent with the calculated heat released to the arm; e.g., the recovery of CW temperatures tended to lead the heat discharged, but this may have arisen from unknown variation in the discharge rates (pumping rates were not recorded). Cloudy weather set in at the end of July, but the onset of lower heat discharged by the BGS occurred when atmospheric conditions were quite uniform.

In later August the drop in BGS output appeared about the same time as a recovery from cloudy conditions.

Water temperatures of PMA were referenced to Station BT (i.e., by subtracting water temperatures at BT from the station of interest; Figure 12). The following observations may be made (Figure 12): water temperatures (half-hourly data) at Station BO, attached to the containment boom some tens of meters from the BGS discharge (Taylor et al. 1999) were up to 3 °C higher than the "background" water temperatures only during the non-summer months, and less than 1 °C during July and August (second plot in Figure 12). These water temperature variations from "background" are within the level of daily variability in water temperatures throughout the arm, as is clear from Figure 12. Water temperatures at ES (~350 m downstream of the BGS discharge), showed little of the seasonality noted for Station BO above, and mean temperatures were only 0.1 °C higher than BT over May to October 1998 period (4th plot in Figure 12). Monthly mean temperatures were higher at BO compared to Stations BT, ES, and RP; a trend that diminished with depth and largely disappeared below 5 to 8 m depth (Taylor et al. 1999). Note that RP is across the arm from the BGS, a distance of some 800 m but possibly within the effect of the clockwise circulation from the BGS (Seaconsult 1995). Mean temperatures for the June to October 1998 period are indicated in the lower left corner of each plot, with standard deviation. This summer-fall mean temperature at BO within 70 m of the BGS discharge is 0.8 °C higher than at BT at the BGS intakes, and 0.7 ° to 1°C higher than other stations in the arm. Mean temperatures at Stations BT, ES and RP are similar, with 0.1 °C. In mid-summer, there was little correlation apparent between the variation in BGS heat released and arm water temperatures (Figure 13).

Cross-correlation of Burrard Generating Station operational data and water temperatures

We wished to detect the influence (in time) of the BGS heat discharge on nearby water temperatures, or alternatively, to see if we could detect the time required for the influence of the BGS discharge to propagate around PMA. We used a simple cross-correlation technique to see if the BGS variability noted in late July 1998 (period "B" in Figure 11) was reflected in similar variability in water temperatures. Details are given in Taylor et al. (1999).

While the effect of the BGS CW discharge was small but apparent in monthly mean temperatures for nearby stations, our simple cross-correlation analysis showed that, on a scale of an hour to a few hours, there was little variability in the nearby water temperatures (BO, ES, RP) that correlated with variability in the BGS operational level. This may be due to the time-scale on which the BGS variability is recorded (4-hour intervals) and the rapid mixing accompanying the large volume and discharge rate of the outfall cooling water.

EFFECT OF MUDFLATS ON WATER TEMPERATURES

An extensive analysis undertaken by Fissel et al. (1998) quantified the thermal effect of Rocky Point mudflats on the waters of PMA. That analysis was based on specific instrumentation installed on the mudflats during late summer, 1997. Because of the limited mudflat observations in the present program, the thermal contribution of the mudflats and shallows to the thermal regime of PMA are reviewed here, for completeness. Last year's observations and calculations demonstrated that two principal mechanisms were involved. Firstly, export of water from the mudflats and shallows along the shorelines to the main body of Port Moody Arm, twice a day due to tidal action (tidal prism); the 1997 observations indicated that such shallows have higher temperatures than regional surface waters in summer (Figure 14). These higher temperatures may develop because of higher albedo due to the proximity of the underlying dark mud to the sea surface and the effect of a rising tide flooding over a warm, subaerially exposed dark mud surface. Secondly, with respect to thermal storage within the mud of the seabed, subsurface temperatures within the mud vary seasonally due to thermal forcing of the overlying water or air. This represents a storage of "summer heat" that is released weeks to months later.

Thermal effect of shallows and the tidal prism

The earlier analysis (Fissel et al. 1998) concluded that the effect of shallows is a significant contribution to the summer heat budget of PMA. Figure 14 shows that 14-day mean water temperatures measured on the mudflats (i.e., not including mud surface temperatures when the mudflats are drying) were up to 1.37 °C higher than nearby sea surface temperatures in non-mudflat areas from June to October 1997 (mudflat data were not available beyond this period). This temperature enhancement, and the mean volume of water covering all the mudflats and shallows surrounding PMA were used to compute the net heat contribution of the shallows to the heat budget of the arm [see calculations in Fissel et al. (1998)] and Table 4.

This heat budget calculation for summer 1997 showed that the additional heat provided to PMA by the twice-daily export of the tidal prism overlying the shallows and mudflat was greatest during early August, being about 80% of the heat discharged to the arm by the BGS operating at typical summer levels. Earlier and later in the summer, the enhanced water temperatures on the mudflats was less than in August (Figure 14), so the heat exported to the main body of water was also less. Cumulatively over the mid-June to early September 1997 period, the shallows contributed additional heat to the arm equivalent to about 25% of the heat discharged by the BGS (Table 4).

Thermal storage in the subsurface mud

The earlier analysis concluded that the effect of thermal storage deeper in the seabed of the mudflats is a minor contribution to the summer heat budget of PMA (Fissel et al. 1998). The effect is that a small quantity of heat is stored in the subsurface seabed in the summer and released during the following weeks or months in the fall and winter (see curve 7 on Figure 4.15 in Fissel et al. 1998). A multithermistor temperature probe installed at Station MF in late summer 1997 enabled a model to be developed and an estimation of this effect (Fissel et al. 1998).

The heat budget calculation showed that absorption of heat by the seabed of the mudflats in the summer represented a small loss of heat from the waters of PMA, but this was minor, equivalent in magnitude to about 3% of the heat discharged by the BGS under normal summer operations.

ANALYSIS OF THE THERMAL REGIME OF PORT MOODY ARM

The temperature of the seawater in PMA is determined by a variety of natural processes and the effects of the surrounding population and industry. A detailed description is given in Fissel et al. (1998), and a brief introduction is provided here.

Figure 15 illustrates the contributions of the major influences that control the seawater temperatures and the thermal state of the arm. Various modes of heat exchange with the overlying air and atmosphere comprise the dominant natural processes. Tidal action with Burrard Inlet represents a major exchange of water and heat between the arm and the larger Burrard Inlet/ Indian Arm system. Tidal action across the mudflats represents a significant heat exchange with the main body of water in the summer. Other natural processes, such as run-off from the surrounding land, also represent water and heat exchange with the arm, but in comparison are believed to be much smaller for this particular basin. Finally, the heat discharged to the arm by the BGS via its use of seawater for cooling is substantial.

The processes depicted schematically in Figure 15 consist of the following:

(1) incoming solar short-wave radiation (Q_s, heat absorbed by water depends on measured incoming radiation and albedo of water);
(2) incoming long-wave (infrared) radiation and "back radiation" from the water (Q_L, depends on air and sea surface temperatures, humidity and cloudiness);
(3) convective heat transfer with the overlying air, i.e. sensible heat flux (H_s, depends on contrast in air and sea temperatures, and wind);
(4) evaporative heat loss, i.e. latent heat flux (H_L, depends on contrast in humidity between sea surface and overlying air, and wind);
(5) heat exchange via tidal action (tidal prism) with the shallow "over-heated" water in the shallows and mudflats ($Q_{shallows}$);
(6) heat sequestered in the subsurface mud of the mudflats during summer and released weeks to months later (Q_{mud}); and
(7) heat discharged by the BGS (Q_{BGS})

The quantitative contribution of each of these processes was calculated from the parameters indicated, using the data set of water temperatures, meteorological parameters and BGS operational data amassed for this project. The individual atmospheric processes (1 to 4, above) combined to give a net value, Q_{net}, as shown in the equation at the top of the Figure. Further details, and the methods and formulas used to calculate the contribution of these processes to the heat budget of PMA are given in Fissel et al. (1998).

A principal goal of the 1998 study was to use the water current measurements to quantify the contribution of tidal exchanges to the heat budget of PMA. Modifications to the water temperature measurement program and the deployment of a current measurement instrument enabled progress towards this goal.

The conceptual heat balance model for PMA, as illustrated in Figure 15, is:
$Q_{residual} = Q_{net\ atmospheric} + Q_{tidal} + Q_{shallows} + Q_{mud} + Q_{BGS} - Q_{water}$ (eq. 1)
which should balance to zero, i.e. heat storage in the seawater of the arm should reflect the natural heat exchanges and the input of the BGS. The method of calculating these various terms was discussed in Fissel et al. (1998); a brief summary is given in Appendix C. The algebraic signs of the natural exchanges and the heat storage term will depend on the season and/or period of time being considered (the BGS term will always be positive).

For this section, we first calculated the cumulative heat budget terms for the summer 1998 data and added to those given in Fissel et al. (1998) for the summers of 1996 and 1997. Next, the heat loss due to currents and tidal action was considered in a detailed heat budget analysis for the month of October 1998, during the time when the current meter was deployed. Problems in extrapolation of these October results to summer conditions are discussed. An analysis of possible errors in the calculation is presented in Appendix D.

SUMMER HEAT BUDGET OF PORT MOODY ARM - UPDATE TO 1998

In Fissel et al. (1998), the summer heat budget of PMA was calculated by a cumulative summing of the heat exchanges with the water over the previous two summers, specifically from

mid-June to early September of 1996 and 1997. The results were presented as Figures 5.18, 5.19 and 5.20, and summarized in Table 5.2 in Fissel et al. (1998). In this section, the same calculation is undertaken for summer 1998. The three figures will be updated by adding the 1998 heat budget results, to facilitate a comparison from one year to another.

Cumulative heat storage, Port Moody Arm

For the 1996 and 1997 analysis, the cumulative heat exchanges are shown for two areas of PMA: the main area generally east of Petro Canada (Station PE) which includes the BGS and most of the mudflat areas, (Figure 16) and, the "mixing area" west of PE and around Gosse Point (Station GP, Figure 17), an area which is assumed to "receive" heat exported from the main area.

As for the 1996 and 1997 results, the cumulative calculation started in mid-June and ended in early September. The following observations are evident from this level of analysis, including the 1998 data. The heat storage in the water (Q_{water}, curve 1) in 1998 was greater than in the previous two years. The peaks occurred in the same 14-day interval in both 1997 and 1998 (water temperatures are highest in early August, Figure 5). Note that the contribution of the mudflats was included in this calculation, because it was assumed that the elevated water temperatures across the mudflats were exported twice daily to the main body of the arm (Fissel et al. 1998). The net cumulative heat exchange with the atmosphere (Q_{net}, curve 2, Figure 16) dominates as a source of heating over the summer. While the cumulative levels attained by early September 1996 and 1997 were similar, the 1998 value was about 10% higher than the previous two years. The contrast in BGS operational levels in 1996 and 1997 was dramatic (the BGS was shut down for much of summer 1996), whereas 1998 cumulative operational levels were about 20% higher than those for the previous year (curve 3, Figure 16). While the BGS cumulative heat discharge to the arm, Q_{BGS}, was similar in magnitude to the net heat gained through natural processes in the summer of 1997, the BGS heat discharge during 1998 appeared to about 20% higher than the natural gains.

A simplified heat balance for the area east of PE is $Q_{residual} = Q_{net} + Q_{BGS} - Q_{water}$ (eq. 2).

The positive residuals shown by open squares (curve 4) in Figure 16 represent net heat added to the water body that is not accounted for in the temperature rise of the water. Note that this residual increased in 1998 due to increases in both natural inputs (curve 2) and BGS heat discharge (curve 3). At the end of the mid-June to early September period, this residual was 7.52×10^{15} J (7,520,000 GJ) or roughly 60% greater than the cumulative heat discharged by the BGS to the arm over the same period.

After considering errors inherent in the various empirical quantities used in the heat budget calculation, Fissel et al. (1998) concluded that most of these residuals represent heat removed from the eastern basin through tidal flushing. Continuing the development in Fissel et al. (1998), $Q_{residual}$ is considered as a heat quantity exported from the section east of PE into the "mixing area" west of PE and around GP (curve 4, Figure 17): $Q_{advection\ to\ GP} = Q_{residual}$.

SUMMARY OF HEAT BUDGET RESULTS

Figure 18 provides a comparison of 1996, 1997 and 1998 heat budget components for the main body of the arm (east of PE), by overlaying the annual calculations from Figure 16 on a single time axis. This figure emphasizes the similarity of the cumulative heat content of the seawater over these three summers, and of the net atmospheric exchanges. The figure also highlights the three very different BGS power levels for these three summers: shut down to very low (1996), moderate (1997) and somewhat higher (1998). Yet, despite this varied BGS operational history, the figure shows that there is no discernible response in overall heat storage in the water body to operating conditions of the BGS. Despite the large thermal input to the basin from BGS in 1997 and 1998, this heat does not appear to be sequestered within the water body longer than a tidal cycle. Similarly, Figure 18 shows that solar and other natural inputs do not appear to be sequestered within the water body longer than a tidal cycle.

The large open symbols in Figure 18 represent the net cumulative heat input to PMA east of Station PE over these three summers: net heat from atmospheric exchanges plus BGS heat less heat stored in the water of PMA. This is the residual heat that needs to be explained. Equation 1 suggests that this should be attributable to $Q_{shallows}$, Q_{mud} and Q_{tidal}.

From the previous study by Fissel et al. (1998), the role of the mudflats in PMA is considerable. Heat from the atmosphere is accumulated on the mudflats while exposed in summer, and then taken up by the ocean water twice each day during high tide conditions (Fissel et al. 1998). The heat accumulated during the summer and stored within the seabed of the mudflats over longer time scales (Q_{mud}) was much smaller in magnitude, being estimated as less than one-tenth of the summer Q_{net} or Q_{BGS} terms (Fissel et al. 1998).

A preliminary calculation demonstrated that most or all of this residual heat is lost through currents and tidal exchange (Fissel et al. 1998). Note that the currents in PMA consist of a large tidal component and a smaller and more variable non-tidal component (due to estuarine effects, runoff, wind stress, BGS-induced circulation, etc.) but for economy the term "tidal" may be used loosely to describe the overall circulation.

The results depicted in Figures 16 and 18 for the area of the arm east of Station PE (i.e., the shallow part of the arm in the vicinity of the BGS), and in Figure 17 for the area west of Station PE (i.e., adjacent to Gosse Point at the outlet of the arm) are summarized for the entire PMA in Table 4.

TIDAL HEAT EXCHANGE BETWEEN PORT MOODY ARM AND BURRARD INLET

Fissel et al. (1998) estimated that 90% or more of the total heat received by PMA from all sources (net atmospheric exchange plus BGS less heat stored in water) is lost quickly from the system, presumably through currents and tidal exchange with Burrard Inlet. This view was supported by a calculation of heat exchange with Burrard Inlet using best estimates of currents at the mouth of the arm (Fissel et al. 1998). However, the available information on ocean currents was very limited, consisting only of a 30-hour time series made in the early 1960's. Also, the

ability to calculate the required horizontal temperature gradients was not optimal in the BC Hydro temperature monitoring network in existence during 1997 (see discussion on temperature gradients, Appendix D).

In the present study, we measured the Q_{tidal} term directly, by making detailed measurements of water currents in October 1998, along with measurements of the horizontal temperature gradient, in the western portion of the arm. This area lies in the narrowest and deepest part of the western arm, an area that is representative of the exchange of water due to currents and tides between PMA and Burrard Inlet proper (area of ADCP, Figure 2). Measurement of currents and temperature gradients in this narrow mouth enabled a calculation of the heat exchange required for equation 1. In this section, we present the computational results derived from the October 1998 measurements, which enabled a much improved estimate of lateral heat movement in this area.

Heat transfer by tides and currents

Heat exchange by currents and tides is a function of the currents and the horizontal temperature gradients through which the currents move:

$$\Delta Q_{tidal} = [\text{mass of water}]\,[\text{specific heat}]\,[\text{temperature change of mass of water}]$$

$$= -[\rho\ A\ U\ \Delta t\ ]\,[c_p]\,[\Delta T] \qquad \text{(eq. 3)}$$

ΔQ_{tidal} = incremental heat energy of mass of water increased by temperature ΔT (J)
ρ = density of seawater = 1027 kg/m^3 [for salinity 35°/$_{oo}$, temperature 5 °C, surface (Gill 1982)]
c_p = specific heat = 3982 J/kg K (Gill 1982)
A = cross-sectional area of channel through which current U flows (m^2)
U = current (m·s^{-1}) along channel (positive to east)
Δt = time interval of interest (s)
$U\Delta t$ = distance traveled (m) = Δx
ΔT = temperature change (°C) of mass of water under consideration (positive to east)

In applying this equation to the tidal exchange in PMA, we defined an arbitrary cross-section through the entrance to PMA, and considered the heat transported by the seawater moving through this section on an hourly basis. Examination of equation 3 and consideration from first principles suggested that the direction (sign) of the temperature difference would determine the direction of heat transport (requiring the negative sign in equation 3).

Calculation of tidal heat transport for October, 1998

The entrance to PMA from Burrard Inlet comprises the channel between Burns Point - Carraholly Point on the north shore and Gosse Point - General Chemical Canada plant on the south shore, a distance of about 1.5 km with a width that varies between 350 m and 500 m (see

Figures 2 and 3). Water depths are greater off Gosse Point (29.4 mean water depth) and Carraholly Point (31.5 m) than immediately west in Burrard Inlet and in all of PMA to the east. This channel represented an ideal location to calculate the heat exchanges by currents and tides.

The ADCP and the temperature loggers deployed in this channel (Stations GW, GE and GC, Figure 3) provided the best configuration for calculating the heat exchange between PMA and Burrard Inlet proper due to currents and tides. As channel currents were measured from September 29 to October 29, 1998, we undertook detailed analyses of the heat transport during this period. For this calculation using equation 3, we considered the volume of water passing through the channel due to tides and currents, and the horizontal temperature gradient through which the volume of water was moving.

Channel cross-sectional area

A north-south transect passing through the ADCP unit was chosen to represent the cross-section of the channel flow in this area (Figure 3). The section extended from shore to shore and from the mean water surface to the seabed. It was divided into six layers (or water slabs) with depth. The first four layers were centered on the depths of temperature sensors at Stations GW and GE, and the lower two were arbitrary (Figure 19):

Layer 1: 0 m < depth < 6.5 m below water surface
Layer 2: 6.5 m < depth < 10 m
Layer 3: 10 m < depth < 13.5 m
Layer 4: 13.5 m < depth < 18 m
Layer 5: 18 m < depth < 22.5 m
Layer 6: 22.5 m < depth < seabed (~ 30 m below mean water level)

Figure 19 shows the cross-sectional areas calculated for each layer. For a discussion of possible errors in measurement of the layer cross-sectional areas, see Appendix D.

Currents

The ADCP measured currents at 10-minute intervals for 1-m depth "bins" relative to the seabed. These data were aligned to project coordinates (i.e., east along channel, north for cross-channel, and vertical). The cross-channel and vertical components were set aside at this point (see below). The 10-minute along channel (east) data were averaged to hourly values to coincide with the on-hour water level predictions (Taylor et al. 1999). The current "bin" depths relative to seabed were converted to depths relative to sea surface using the water level curves (see method, Appendix I). The hourly database of depth-adjusted data was sorted by depths falling within the six slabs or layers (see channel cross-sectional area, above), and averages were taken within each layer. This resulted in the basic data for use in the tidal heat exchange calculation: mean hourly along channel (east) currents for each layer or slab (Taylor et al. 1999).

Horizontal temperature gradients

This gradient was defined as the simultaneous difference in temperature between two stations divided by their horizontal separation; higher temperatures to the east gave a positive gradient. For the October 1998 analysis, Stations GE and GW were used for the gradient (Figure 3) calculation in each layer. Since these stations had no sensors in the lower two layers, the latter were assigned the gradient calculated for layer 4. This was a reasonable approximation, as water temperatures deeper than 5 m to 8 m tended to be nearly isothermal. Temperatures are interpolated to an hourly time base common to the calculated mean currents, and the difference divided by 150 m, the separation of Stations GE and GW.

Current and tidal heat transport by horizontal temperature gradients

Equation 3 is cast in the form

$$\Delta Q_t = -[\rho\ A\ \Delta x\ ][c][\Delta T]$$
$$= -[\rho\ A\ U\ \Delta t\ ][c][dT/dx\ U\Delta t] \qquad \text{(equation 3a)}$$

dT/dx = horizontal water temperature gradient ($°C \cdot m^{-1}$)

Note that for the period of calculation (i.e., hourly intervals), in equation 3a the mean water velocity determines both the volume of water moving through the cross-section and its temperature change as it travels through the horizontal temperature gradient in the section. The positive direction was taken as east (into PMA). Theoretical considerations require that heat transport by the currents is out of PMA (negative) when $T_{GE} > T_{GW}$ (positive temperature gradient) for both positive and negative currents; and heat transport by the currents is into the arm (positive) when $T_{GE} < T_{GW}$ (negative gradient) for both positive and negative currents.

This important result of theory shows that it is the temperature gradient at the mouth to PMA that determines the direction of heat transport by tide and currents. Heat is removed from the arm only when the arm is warmer than Burrard Inlet. For derivation and further discussion, see Appendix D.

Figure 20 summarizes the calculation of heat transport for the upper layer, October 1 - 5, 1998. The first vertical guideline (mid-day October 1) marks the onset of flood tide (defined by current passing through 0, top graph). The following dotted line indicates the start of ebb tide. On October 1, east-going flood currents are accompanied by a positive temperature gradient (temperatures higher at GE than GW, 2nd graph), and the cooler water flooding the arm represents a net transport of heat out of the arm (negative peak on 3rd graph). The positive temperature gradient persists at the beginning of the subsequent ebb tide, and the warmer water leaving the arm transports heat out of the arm (second negative peak in 3rd graph). Note that the heat transport drops to nearly zero when the current passes through zero (the value is not exactly zero since a current = 0 rarely falls exactly on the hour). Towards the end of the next ebb tide, temperature gradients become negative and heat transport is into the arm. The 4th graph gives a sense of the magnitude of the heat being moved, with reference to heat discharged by the BGS into the arm during this period when the BGS was operating at about 60% peak power.

The most notable feature of Figure 20 is the rarity of negative temperature gradients, resulting in little heat being carried into the arm in the upper layer, or upper 6.5 m. Figure 21 illustrates that the opposite situation occurred in the deeper layers, and for the month of October 1998 (Figure 22), heat was predominantly transported into the arm in the deeper layers.

Heat balance for October, 1998

The remaining terms in equation 1 (the net atmospheric exchanges, BGS heat discharge, and the thermal storage in the seawater) were calculated on a cumulative basis for the same period, October 1 - 27, 1998 (Fissel et al. 1998). Figure 23 summarizes the four components of the heat balance for PMA. The heat energy accumulation of each term starts at a value of 0 on October 1. The final net heat accumulation on October 27 is labeled in each graph. The atmospheric and current/tidal exchanges were negative over this period, and the cumulative heat discharged by the BGS was large and positive. The thermal storage in the water was negative (Figure 16), due to the observed decreasing water temperatures during the month. Note that the term Q_{mud} was dropped from eq. 1 for the October 1998 calculation. Lack of data at MM and MF beyond late summer prevented an assessment of the importance of $Q_{shallows}$ in the fall; however, net atmospheric exchanges with the water are negative in the fall, and the term was considered small.

A major accomplishment of the present study was the "balancing" of the heat budget for October 1998 (Figure 24). The major components of the heat budget calculated from the data are shown along the left axis of the bar graph. Above the first horizontal gray line are only heat quantities gained or lost by the water of the arm. The summation of the net atmospheric exchanges, the BGS discharge and the heat lost due to tidal action is the net sum of the heat gained or lost to the water of the arm. For a perfect heat balance, this summation should be reflected in the change in the heat content of the water over the month. In this case, the water lost heat (water temperatures decreased). The difference between the summation of the calculated heat gains and losses, and the change in the heat content of the water, is the residual (equation 1) that represents possible errors in the calculation or processes not accounted for. The figure shows that about 80% of the BGS heat is lost via tidal action, about 20% by atmospheric exchanges, with a modest (but not small) residual that is within our estimate of errors (Appendix D).

Heat is carried out of PMA in the surface water, and heat carried into the arm in the deeper waters, with the net effect being a large outflow of heat from the arm attributable to currents and tidal action (Figure 25). Knowledge of the actual variation of the heat transport with depth is limited by the choice of layers in our model. It should be noted here that calculations in layers 5 and 6 are based on mean currents at these depths but on temperature gradients at the depth of layer 4 (see horizontal temperature gradients, above).

Analysis of errors in the calculation of currents and tidal heat transport

A summary of possible sources of error is provided here (see also the discussion in Appendix D). We considered two sources of error: random measurement errors, which can be estimated with confidence, and systematic or bias errors, which are less well known.

The most significant random error was the resolution of the temperature sensor in the StowawayTM loggers (+/- 0.1°C). Since differences in temperatures are used in the temperature gradient calculation, this can lead to a possible error of 14%. The locations of Stations GW and GE were not well known, but of more importance to the calculation was their separation, which was estimated as 150 m +/- 15 m and represented a 14% uncertainty to the temperature gradient calculation. Overall, the random errors might account for a 21% error in the calculation of current and tidal heat transport (Appendix D).

Systematic errors are attributed largely to the misrepresentation of the system by our experimental setup and assumptions of the simple model. We believe that a good representation of the currents past Carraholly Point was made, and that the major representational error arises from the segmentation of the water mass into only six layers due to limited temperature measurements. This could have resulted in an error of possibly 5%. A larger error, possibly as much as 14%, might arise from a systematic offset in calibration between the two temperature loggers being used for the gradient calculation. Other errors were small, and their overall impact on equation 3 was estimated as an error of no more than 21%.

In summary, the statistically combined random and systematic uncertainty in the current/tidal heat transport Q_{tidal} was 30%. The uncertainty in remaining terms in equation 1 was about 25% for $Q_{net\ atmospheric}$, 10% for Q_{BGS} and 15% for Q_{water} (Fissel et al. 1998). Combining these uncertainties statistically suggests that the overall uncertainty in the heat budget residual of 534,000 GJ was about 45% (i.e., about 240,000 GJ, over the month of October 1998). For a benchmark, this quantity is equivalent to about 12% of the heat discharged by the BGS in October 1998.

Comparison of October 1998 heat budget terms to those of summer

Table 4 compares the various components of the heat budget including current and tidal exchange as calculated for October 1998 to the magnitudes of the components calculated for the longer period in the summer, mid-June to early September 1998 (Figure 17). This table is similar to Table 5.2 in Fissel et al. (1998), where the areas "east of PE" and "west of PE" served to demarcate the shallower part of PMA influenced by the BGS discharge from the deeper, western sector thought to be a mixing zone between the shallower arm and Burrard Inlet [the location of the boundary between these two sectors is shown in Figure 5.17, (Fissel et al. 1998)]. The division was retained here so that the 1998 summer heat budget calculations were consistent with the analysis of the previous report. In addition, Table 4 includes summer results prorated to a 27-day time interval in order to compare with the similar-length period of the October 1998 results.

It was not possible to estimate the tidal heat transport for times other than October 1998, due to the lack of water temperature monitoring stations in the channel between Carraholly Point and the General Chemical Canada plant, from which representative horizontal temperature gradients could be calculated. For the summer heat budget calculations, summation of the net atmospheric exchanges and the BGS heat discharge left a large residual (equation 2, Table 4, Figure 16) that could only be surmised as being the heat loss due to tides, on the basis of the very small quantity of heat stored in the seawater.

Columns 5 and 6 in Table 4 allow comparison of October 1998 values to an equal-length period in the preceding summer. The net atmospheric heat exchange with PMA turned from a gain in summer to a loss in October, and the water body changed from gaining heat to losing heat during the summer-to-fall transition. BGS heat discharge was higher in the fall of 1998 than in the preceding summer, because operating levels were higher (Appendix F.2; Taylor et al. 1999).

"Unexplained" in Table 4 represents possible heat gained or lost by the arm through processes that are generally unknown and probably small. Hydrological runoff from the several streams entering the arm may be one such process that is believed to be insignificant and was not considered in the heat budget calculation. If these unexplained heat gains/losses and errors calculated for October are similar in magnitude for the prorated summer season (i.e., 531), a simple algebraic calculation suggests that the tidal heat loss component in the summer could be substantially higher ($2956 - 531 = 2425 \times 10^3$ GJ per 27-days) than calculated in October (1563×10^3 GJ per 27-days).

Use of October currents and tidal analysis to calculate summer heat budget

There are two problems to be recognized for a "closure" of the heat budget calculation at other times of the year, similar to that achieved in October 1998. First, there is the need to predict currents outside of the period of measurements, and second, the availability of suitable stations to calculate horizontal temperature gradients must be considered. The BC Hydro water temperature monitoring network enables the calculation of all other terms in equation 1.

Predicted currents

The heat transport calculated from the measured currents and temperature gradients consists of 3 components:

Heat transport = tidal + variable residual + mean current heat transport (equation 4)

The mean and variable residual arise from non-tidal components (estuarine effects, wind stress, runoff, BGS-induced currents, etc.). Based on the currents measured throughout October 1998 and using tidal prediction software (Foreman 1977), currents may be predicted for the same period in October, with or without the mean current for that month. The residual currents are small, as can be seen by the overlay of the hourly predicted and observed currents in Appendix I.8 (Taylor et al. 1999), the mean current is somewhat larger, as is apparent in the equivalent figures in Appendix I.9 (Taylor et al. 1999). To use the tidal prediction "fit" obtained from the October 1998 data for other times requires independent knowledge of the variation in the mean currents and the residual, at these other times. Because of their source, the mean and residual non-tidal components in equation 4 are variable from one time of the year to another, and from one year to another. The important implication for a heat budget calculation is that a portion of the heat transport occurs via mean currents and other non-tidal components that may not be known outside of October 1998.

For demonstration, we considered the magnitude of the problem by comparing the heat transport calculated from observed currents to that calculated from predicted currents for October 1998. In Table 5, the second column is the observed heat transport over the period October 1 - 27, 1998, calculated from the observed currents and horizontal temperature gradients. Column 3 lists the predicted heat transport for this period based on the predicted currents including the mean, and column 4 shows the corresponding predicted heat transport based on predicted currents minus the mean current. The difference between columns 3 and 4 shows that about 20% of the overall heat transport is attributable to mean currents in October 1998.

Currents predicted for other times of the year may be used to calculate the tidal heat transport, but an unknown quantity of heat may be transported by the mean current and a non-tidal variable component. For instance, high seasonal runoff more typical of a normal estuarine environment would produce a significant mean outward flow and heat transport that would be unaccounted for by twice daily tidal flushing; this extreme is not expected for PMA. Since most of October 1998 preceded the rainy season, October should be a reasonably close analog to summer current conditions for PMA. Thus, currents may be predicted for summer if a possible 20% uncertainty in the predicted currents can be tolerated.

Horizontal temperature gradients

The second and more critical problem for this study was the need for water temperature stations suitable for calculating horizontal temperature gradients representative of the Carraholly Point – General Chemical Canada plant channel for which the currents are predicted. For the October 1998 calculation, this was achieved by installing Stations GW and GE specifically for the project in an optimum location at the entrance to PMA, near the same location as the current measurements were made. This provided well-constrained data for the calculation. However, at prior times in the absence of these stations, possible station pairs that might have been used are BT-GP and PE-GP, but the separation between these station pairs is more than an order of magnitude greater (2780 m and 2250 m, respectively) than that between Stations GW and GE. The suitability of such station pairs to calculate heat transport is questionable on two counts. First, the geometry is unsatisfactory to approximate the channel flow assumed in our simple model: the width between these station pairs varies by a factor of two, the depth decreases by a similar factor from one to the other, and significant vertical currents would be expected. Secondly, while such larger separation would reduce errors in measurement of the horizontal temperature differences (Appendix D), each station of the pair is representative of two distinctly different thermal environments. Finally, the six-layer structure for water depth is suitable at only one end of each station pair.

Recognizing these shortcomings, for demonstration purposes, we used currents predicted for October 1998, with horizontal temperature gradients using Stations BT-GW and PE-GW, to predict the current/tidal heat transport in the upper two layers for October 1-27, 1998. These values were compared to our earlier analysis using measured currents and temperature gradients from Stations GE-GW for the same period. Details are given in Taylor et al. (1999), and only a summary is provided here.

The heat transport quantities calculated in this way for the October 1 - 27, 1998 period were up to a factor of 10 less than those obtained using Stations GE-GW (Taylor et al. 1999). In conclusion, for PMA, we might expect an error of as much as 20% in these computations due to lack of knowledge of the non-tidal currents. A potentially much larger, unknown and clearly unacceptable error must be associated with temperature gradients from ill-positioned stations. It is clear that stations are needed in the vicinity of the current prediction station (ADCP) for calculating summer tidal and current heat transport.

Calculation of implied temperature gradients using a single station

Differences between temperatures measured at a single station over a certain period of interest are a possible alternate approach to estimating temperature gradients, and hence the tidal heat transport. This method was used to estimate magnitudes of tidal heat transport in Fissel et al. (1998). It requires a different implementation of equation 3, and is based on the concept that a water mass brought in on flood tide originates in the large reservoir of Burrard Inlet west of PMA, that this mass experiences an exchange of heat during its residence time in the arm, and that the ebb tide exports this heat to Burrard Inlet. The calculation may be done also on an hour-by hour basis. Further discussion and a demonstration of the method, together with a comparison to the preferred two-station method of calculating horizontal temperature gradients is detailed in (Taylor et al. 1999).

The concept assumes that sufficient mixing in the larger Burrard Inlet proper does not allow heat to be re-imported to the arm. It considers that temperature changes occurring at a single point over a short period (hour, or ebb portion of tidal cycle) correspond to the actual temperature change experienced by a parcel of water defined in volume by the currents and tides, during the same interval. This is a questionable assumption.

We made a number of attempts to calculate the heat transport by this single-station method, but found that it led to values one-half to one-tenth of those obtained by the more accurate 2-station gradient method. In addition, the variability was much greater in the single-station method. Most importantly, the single-station method was not consistent in its prediction of the vertical distribution of the heat transport. Hence, we did not consider the single-station method as a viable option for calculating the tidal heat transport.

DISCUSSION

The direct measurement of heat transport by water currents has shown that currents and tides are the dominant mechanism for heat loss from PMA, and hence for regulating the water temperatures therein. The analysis has shown that the direction of heat transport at any particular depth is governed by the horizontal water temperature gradient at that depth. Because of the diurnal variability in the vertical stratification of water temperatures, heat may be lost or gained by the arm depending on the horizontal temperature gradient existing at a particular depth. Over the month of October, heat transport calculations at the entrance to the arm showed that there was

a loss of heat through tidal action in the upper 6 m, and a smaller gain of heat in the deeper water. The net effect was a heat loss from the arm due to currents and tides alone equivalent to about 80% of the BGS heat discharge. Additional heat loss from the arm during October 1998 occurred through a net loss to the atmosphere.

IMPLICATIONS OF THE 1998 STUDY TO EXISTING HYDRODYNAMIC MODELS

These findings of the 1998 study have major implications to the use of numerical oceanographic models to represent the movement of heat throughout the arm and its exchange with Burrard Inlet. The existing 2-dimensional hydrodynamic model for PMA and the BGS discharge (Seaconsult 1995) computes depth-averaged circulation in two horizontal dimensions, averaged over water depth. The model uses the physics of conservation of mass and momentum to predict currents throughout PMA, and includes the effect of the cooling water discharge rate from the BGS. The hydrodynamic model appears to have skill in representing current and current patterns throughout the arm (as confirmed by circulation paths identified through dye tracer studies). However, as presently configured, Seaconsult's hydrodynamic model provides only a weak mechanism for heat loss from the arm via tidal action, largely due to the model's treatment of the boundary conditions at the entrance to the arm. The discussion in Fissel et al. (1998) and the major discoveries of the nature of heat loss from the arm by currents in tides in the present study amply demonstrate that the present hydrodynamic model is not adequate to represent the thermal processes that we now know are occurring.

For a numerical model to be useful in predicting thermal exchanges, the model must meet three major requirements, amongst others, specific to the PMA situation. It must attain realistic levels for the current and tidal heat transport in the western arm, model the very significant vertical variations in the tidal heat transport identified in the present study (Figure 25), and incorporate horizontal exchanges with Burrard Inlet proper, west of Gosse Point.

Substantial effort is required in the development of such a new hydrodynamic model, its validation and refinement. Some modest amount of additional data would be required to constrain the model. For example, water temperatures in Burrard Inlet are needed to provide a western boundary condition to the model.

EFFECT OF THE BGS ON NEARBY WATER TEMPERATURES

It has been demonstrated by these studies that the BGS discharge of cooling water has a limited impact on water temperatures in PMA. The magnitude of the impact depends on which data set or statistic is used, being lower in the longer-term means. Also, it is clear that there is a not-unexpected greater impact in the "near-field" zone within 100 m of the BGS, and a smaller impact within the eastern portion of PMA. In both cases, the thermal disturbance appears to be limited to the surface waters. Also, the magnitude of the impact of the BGS on water temperatures in PMA appears to lie within the level of natural variability on daily and inter-annual time scales.

At the level of monthly mean and 14-day mean water temperatures, the impact of the BGS is limited to an increase of mean summer water temperatures throughout the arm of 1 °C to 2 °C, only in the upper, approximately 5 m water depths. These magnitudes were supported further through a comparison with a year when the BGS was shut down until near the end of the summer. To put these magnitudes in perspective, it appears that the effect on the arm of "*El Nino*" in 1997 - 1998 was of the order of 2 °C. In the "near-field" zone, the same monthly and 14-day means record an impact of a few tenths of a degree, again only in the upper few meters. This impact is most obvious on the monthly water temperature contour plots in the spring and fall, when the contrast between BGS discharge temperatures and ambient water temperatures is greater.

The level of the half-hourly water temperature measurements presents a more instantaneous measure of the impact of the BGS. Half-hourly water temperatures within a few meters of the surface at the containment boom (within 70 m of the BGS heat discharge) were up to 3 °C higher than the "background" water temperatures during the non-summer months, and less than 1 °C during July and August (second plot in Figure 12). To put these values in perspective, all stations throughout PMA showed a daily variability of about 3 °C in summer that arises from natural atmospheric heating.

A simple cross-correlation analysis showed that, on a scale of an hour to a few hours, there was little variability in the near-field water temperatures that correlated temporally with variability in the BGS operational level. This may be due to the time-scale on which the BGS data is recorded (4-hour intervals) and the rapid mixing accompanying the discharge velocity of the outfall cooling water.

EXAMINATION OF THE BGS MAXIMUM GENERATING SCENARIO

At present, the BC Hydro's operating license limits the temperature of the cooling water discharge to a maximum of 27 °C, and the cooling water discharge rate to 1.7×10^6 m^3 d^{-1}. These license limits are most restrictive to BGS power production in the late summer, when cooling water intake temperatures are at their highest of the year (Figure 26a, based on 14-day means). For purposes of this study, these temperature/pumping limits also may be cast as a limit on the quantity of heat discharged to PMA by considering the temperature spread between 27 °C and the intake temperatures (at Station BT), with the licensed (maximum) pumping rate (Figure 26b).

As part of this project, it was requested by BC Hydro that the thermal impact upon PMA of operating the BGS at increased power levels be addressed. Specifically, the thermal implications of increasing the cooling water discharge to a 100% capacity (a discharge of heated cooling water of 2.5×10^6 m^3 d^{-1}). This represents an increase of 47% over the present licensed pumping rate. Such an increase, while still maintaining the cooling water temperature limit, would allow an equivalent increase in maximum permissible heat discharge to PMA, and, presumably, a similar increase in BGS power output.

We have shown that current and tidal heat transport is effective in regulating water temperatures in PMA. That is, tidal action is the dominant natural mechanism that limits the

increase of water temperatures attributable to the BGS operation to 1 °C - 3 °C at most, throughout the year. Further, we have shown in the October 1998 calculations that current and tidal heat transport alone is capable of removing most of BGS discharge heat when the latter is operating at approximately 60% (575 MW) of its design generating capacity. While the tidal heat transport could not be calculated specifically for summer, there was strong observational evidence in the water temperature data set to show that tides and currents also regulate water temperatures during the critical summer season, when atmospheric heat inputs to the arm are much higher, than at other times of the year.

It was suggested that if the combined unexplained heat gain/loss and errors in the calculation for October 1998 are similar in magnitude to those for a similar-length period in the summer, then the tidal heat loss component in the summer might be half again as high as the tidal heat loss calculated in October, under present BGS loading. This suggests that PMA could cope with a fully loaded (100% design capacity) BGS CW discharge through much of the year, except possibly in summer.

Figure 26b shows the actual heat discharged during the summer by the BGS over the four years 1995 to 1998, and the maximum heat that might be discharged under the present operating license (cooling water discharge at 27 °C, 1.7×10^6 m^3 d^{-1}). This figure shows that there was unused heat discharge capacity under the present license, particularly in the summers of 1997 and 1998.

SUMMARY AND CONCLUSIONS

In this study, oceanographic and meteorological data sets gathered in PMA during 1998 were processed, along with operational data from the BGS, and integrated with the extensive database developed previously (Fissel et al. 1998). In all, water temperature data were available for varying periods from some 14 stations at depths to 27 m around the arm (Figure 2, Table 1, 2). Analyses undertaken in the report by Fissel et al. (1998) have been updated with this additional data.

The deployment of an Acoustic Doppler Current Profiler for the month of October 1998 in the narrow entrance to PMA (Figures 2 and 4) provided new and critical information. Precision and detailed water currents measured with this installation, and data from nearby water temperature stations have enabled for the first time a well-constrained calculation of the heat transport in and out of the arm by currents and tides. The results for October 1998 confirm that currents and tidal action play a dominant role in the removal of heat from the waters of PMA; this heat loss occurred via currents and tidal action in the upper 6 m, amounting in this layer alone to about twice the BGS heat discharge (Figure 25). However, at mid-depths, the arm gained heat by currents and tidal action between 6 m and 10 m, and to a lesser degree at greater depths. The cumulative result of the heat exchange calculation over the entire water column was a large net export of heat from PMA to Burrard Inlet.

As a benchmark, the above calculations indicated that a quantity of heat equivalent to more than 80% of the BGS heat discharged to PMA in October 1998 left the arm due to currents and tidal action (Figure 24). Calculations of the atmospheric heat exchanges for October 1998 showed that there was an additional loss of heat from the water body to the atmosphere, sufficient not only to account for the "remaining 20%" of the BGS discharge heat, but also to remove heat from the water body and yield the decreasing water temperatures observed in the arm over the month.

The integrity of the above results is assured in the present study through achieving, for the first time, a balancing of the overall heat budget for the water of PMA (Figure 24). For the month of October 1998, the contribution of various atmospheric heat exchanges were calculated from the local meteorological and water temperature data, and the heat discharged to the arm by the BGS was available from operational data. The estimated error in these calculations is a quantity of heat equivalent to about 12% of the BGS heat discharge.

The following are the major findings and conclusions from this year's study, in order of appearance in this report:

1. Extensive monthly and 14-day statistics (mean, standard deviation, minimum and maximum) were calculated for the water temperatures and meteorological parameters representative of PMA (Taylor et al. 1999).

2. Contour maps of monthly mean water temperatures for PMA were prepared for depths 0.5 m, 2 m and 5 m, for the period February to September, and for noon October 29, 1998 (Appendix A). These maps depict graphically the variation of temperatures throughout the arm, particularly the higher temperatures in the main body of the arm and the lower temperatures in the western channel around Carraholly Point. Slightly elevated monthly mean temperatures (no more than a few tenths of a degree) observed within 100 m of the BGS discharge are more obvious on these contour maps in non-summer months, and only in the upper few metres water depth, because of the greater contrast between BGS cooling water discharge temperatures and ambient seawater temperatures.

3. Contour plots of monthly mean water temperatures with water depth for a transect along the length of the arm were prepared for the period June to September and noon October 29, 1998 (Appendix B). Any influence of the BGS thermal plume on water temperatures within the arm is discernible only in the upper few metres of these vertical sections.

4. During summer, monthly mean water temperatures at a depth of 2 m at eastern stations are some 2 °C - 3 °C higher than those at Gosse Point, at the western entrance to the arm. Summer maximum monthly temperatures at these stations and depth are up to 5 °C - 6 °C higher. These observations reflect the mixing with the adjacent Burrard Inlet and Indian Arm to the west, while the summer water temperature gradient to the east and towards the head of the arm may be ascribed largely to the distance and lessening exchange with Burrard Inlet, and the effects of the large mudflats. Mid-winter monthly mean temperatures are similar

throughout the arm, although some winter minimum temperatures are lower in the arm than at Gosse Point (Figure 6).

5. Water temperatures to depths of 8 m in mid- to late-winter 1997-1998 were about 2 °C higher than in the two previous years. This trend continued in 1998 to the spring and summer, and was possibly due to strong *El Nino* conditions, resulting in a warming of the north Pacific Ocean and adjoining inland waters (Figure 8, Figure 9).

6. The ADCP deployment during October 1998 provided the precision measurements of current velocities off Carraholly Point needed for the heat transport calculation.

7. The cumulative heat budget for the summer period, mid-June to early September, was calculated for 1998 and compared to the previous two years (Figure 16). BGS power levels were very different for each of these three summers. Yet, there is a lack of basin-wide response to operating conditions at the BGS and heat did not appear to be sequestered within the water body for longer than a tidal cycle.

8. The water temperature monitoring program provides strong observational evidence that arm water temperatures are regulated by natural processes. In the summer, the arm starts losing heat through natural processes in late July – early August, regardless of BGS operational levels (Figure 16, 11, 12).

9. The overall heat budget for PMA for October 1 - 27, 1998 "balanced" to within 531,000 GJ (Table 4). This residual comprises smaller heat sources and sinks not accounted for in the analysis, and errors. About half of this amount was the estimate of errors. The heat budget calculations indicated that a quantity of heat equivalent to more than 80% of the BGS heat discharged to PMA in October 1998 left the arm due to currents and tidal action (Figures 24 and 25). There was an additional loss of heat from the water body to the atmosphere, sufficient not only to account for the "remaining 20%" of the BGS discharge heat, but also to remove heat from the water body and yield the decreasing water temperatures observed in the arm during October 1998.

10. The thermal discharge from the BGS at normal operating levels has limited impact on the temperature of surrounding waters of PMA. Within 100 m of the BGS, mean monthly water temperatures are no more than a few tenths of a degree higher than surrounding background water temperatures, and only within the upper few metres of the water column. Water temperatures measured half-hourly within 70 m of the BGS discharge point may be as much as 1 °C - 3 °C higher than BGS intake temperatures (Figures 12, 13); however, these values are about the same as the daily variation in water temperatures observed throughout the arm (Figures 11 and 12). Using a simple cross-correlation technique and using 4-hour BGS heat discharge data (Taylor et al. 1999) variations in heat discharged by the BGS were shown not to be correlated with changes in water temperatures throughout the water column at nearby stations. This suggests that mixing of the BGS discharge with the surrounding water in the "near-field" occurs quickly and efficiently.

11. Current and tidal heat transport alone is capable of removing most of BGS discharge heat when the latter is operating at approximately 60% (575 MW) of its generating capacity, as shown by the October 1998 calculations. There is evidence that tidal heat loss in the summer may be substantially higher than calculated in October, under present BGS loading. This suggests that PMA could accommodate with the thermal discharge resulting from the BGS operating at 100% capacity through much of the year, except possibly in summer.

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REFERENCES

BC Hydro. 1996a. Plan for environmental impact study: receiving waters associated with cooling water discharged by the Burrard Thermal Generating Plant (Permit PE-07178). Prepared for BC Ministry of Environment Lands and Parks, and Burrard Inlet Environmental Review (BERC) Subcommittee. December, 1996.

BC Hydro. 1996b. Burrard Thermal Generating Station. BC Hydro, Burnaby, BC.

Beak. 1976. A biological and physio-chemical of Burrard Inlet. Report for BC Hydro by Beak Consultants Ltd., Vancouver, BC.

Beak. 1980. Burrard Thermal Generating Plant liquid effluents – environmental impact assessment. Report for BC Hydro by Beak Consultants Ltd., Vancouver BC.

Canadian Hydrographic Service. 1992. Hydrographic Chart 3495, Vancouver Harbour Eastern Portions. Ottawa, ON.

Davidson, L.W. 1979. On the physical oceanography of Burrard Inlet and Indian Arm. M.Sc. thesis, Institute of Oceanography, University of British Columbia, Vancouver, BC.

Elliott. 1965. A study of the heat budget components for the British Columbia and S.E. Alaska coast. Manuscript Report No. 18, Institute of Oceanography, University of British Columbia, Vancouver, BC.

Fissel, D.B., M. MacNeil, and A.E. Taylor. 1998. A study of the thermal regime of Port Moody Arm in relation to the Burrard Thermal Generating Station. Volume I: Report, and Volume II: Appendices. Report to BC Hydro, Burrard Thermal Generating Station, Burrard Upgrade Project Office, Port Moody, BC.

Foreman, M.G.G. 1977. Manual for tidal heights analysis and prediction. Pacific Marine Science Report 77-10, Institute of Ocean Sciences, Sidney, BC (Revised July 1996).

Gill, A.E. 1982. Atmosphere-ocean dynamics. Volume 30. *In* International geophysics series. *Edited by* W.L. Donn. Academic Press, New York, NY.

Greenbank, J.D., S.L. Rendek, and I.K. Birtwell. 2001. Salmonid migration in tributaries of Port Moody Arm, Burrard Inlet, BC. Can. Man. Rep. Fish. Aquat. Sci. 2557: 47 p.

Henry, M. 1998. Unpublished data. Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC.

Hodgins, D.O. 1993. Temperature and residual chlorine measurements in Port Moody Arm, September 16, 1993. Prepared for BC Hydro, Burnaby, BC.

Hodgins, D.O. and A.J. Webb. 1991. Determination of residual chlorine in Burrard Inlet originating from the Burrard Thermal Generating Plant. Prepared for BC Hydro, Vancouver, BC.

Laval, B. 1997. Port Moody Arm: temperature and salinity field mapping in the vicinity of the Burrard Thermal Generating Station, using the Autonomous Underwater Vehicle ARCS: data report. Underwater Research Laboratory, School of Engineering Science, Simon Fraser University, Burnaby, BC.

Patrick. 1957. Report on the Port Moody-Coquitlam sewerage survey. Greater Vancouver Sewerage and Drainage District, Vancouver, BC.

Perkins, E.J. 1974. The biology of estuaries and coastal waters. Academic Press, New York, NY.

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. 1989. Numerical recipes, the art of scientific computing (Fortran Version). Cambridge University Press, New York, NY.

Seaconsult. 1995. Receiving water impact assessment for the Burrard Thermal Generating Plant. Prepared for BC Hydro, Burnaby, BC.

Taylor, A.E., D.B. Fissel, J. Hibbs, and A. Tsoi. 1999. Burrard Thermal Generating Station cooling water impact study: thermal regime of Port Moody Arm, 1998. Volume II: Appendices E-J. Report to BC Hydro, Burrard Thermal Generating Station, Burrard Upgrade Project Office, Port Moody, BC.

Waldichuk, M. 1964. Water exchange in Port Moody, British Columbia. Presented at the Annual Meeting of the American Society of Limnology and Oceanography.

Webb, A.J. 1992. Residual chlorine in Port Moody Arm of Burrard Inlet originating from the Burrard Thermal Generating Plant: October 1991 Survey. Prepared for BC Hydro, Vancouver, BC.

Table 1. Port Moody Arm water temperature stations and depth (m) of sensors for various years, 1995-1998[1].

(m)	BD	BT	BO	ES	IN	MM	MF	RK	PC	RP	RW	PE	GE	GC	AD	GW	GP	(m)
0						+	+[2]											0
0.1		#		#	#			#	#	#							#	0.1
0.5		●	+	●	#			#	●	●		●					●	0.5
1		#		#	#				#	#							#	1
2		●	+	●	#				●	●		●					●	2
3.5		+	+	+					+	+		+					+	3.5
5		●	+	●	#				●	●		●	▲			▲	●	5
8		●								●	+		▲			▲	●	8
12	#									●	+		▲			▲		12
15													▲	▲		▲		15
20														▲				20
27															▲			27

Symbol:
● = Active – as of late 1998
+ = Active – installed March 1998
▲= Active – installed October 1998
= Inactive – by Spring 1998

[1] Stations ordered clockwise around Port Moody Arm. See Figure 2 for locations.
[2] Also, 8 mud temperatures to 1.6 m depth in seabed (Summer 1997).

Table 2. Locations and depths of BC Hydro's monitoring stations for water temperatures, Port Moody Arm, 1995-1998.

Stn.	Latitude/ Longitude	Location [distance from shore] (m)	Sensor depths (m below water surface)				
North Shore, West to East							
BD	*49° 17' 48" N* - - *12* *122° 53' 44" W*	*BGS Boat Launch*	-	-	-	-	-
BT	49° 17' 55" N 5 8 122° 53' 22" W	BGS Thermal Intakes [~ 50 m offshore]	.1	.5	1	2	3.5
BO	49° 17' 55" N 3.5 5 122° 53' 18" W	BGS Outfall [~ 75 m offshore]		-	.5	-	2
ES	49° 17' 58" N 5 122° 53' 03" W	Esso Refinery Dock [~ 175 m offshore]	.1	.5	1	2	3.5
IN	*49° 18' 02" N* *5* *122° 52' 34" W*	*Ioco Net Pens* [~ 100 m offshore]		.1	.5	1	2
MM	49° 17' 49" N 122° 52' 5" W	Mossom Mudflats 0.0 (water/surface)					
South Shore, West to East							
GP	49° 17' 33" N 3.5 5 8 122° 55' 37" W	Gosse Point [~ 30 m offshore]		1	.5	1	2
GW	49° 17' 26" N 5 8 12 122° 54' 49" W	General Chemical West 15 [~ 50 m offshore]	-	-	-	-	-
AD	49° 17' 28" N - - - 122° 54' 43" W	ADCP instrument - - - 25 [~ 125 m offshore]	-	-	-	-	-
GC	49° 17' 28" N - - - 122° 54' 39" W	General Chemical Centre - 18 23 [~ 120 m offshore]	-	-	-	-	-
GE	49° 17' 26" N 5 8 12 122° 54' 40" W	General Chemical East 15 [~ 50 m offshore]		-	-	-	-
PE	49° 17' 31" N 3.5 5 122° 53' 43" W	Petro Canada [~ 50 m offshore]		-	.5	-	2
RW	49° 17' 33" N 8 12 122° 53' 27" W	Reed Point West [~ 100 m offshore]	-	-	-	-	-	-
RP	49° 17' 34" N 5 8 12 122° 52' 57" W	Reed Point Marina [~ 100 m offshore]	.1	.5	1	2	3.5

Table 2. Locations and depths of BC Hydro's monitoring stations for water temperatures, Port Moody Arm, 1995-1998 (cont.).

Stn.	Latitude/ Longitude	Location [distance from shore] (m)	Sensor depths (m below water surface)				
PC	49° 17' 16" N 5 122° 51' 55" W	Pacific Coast Terminals [~ 30 m offshore]	.1	.5	1	2	3.5
RK	*49° 16' 55" N* *122° 50' 59" W*	*Rocky Point Marina* [~ 30 m offshore]	.1	.5			
MF	49° 16' 57" N 122° 50' 39" W	Rocky Point Mudflat 0m (water/surface) and mud temperatures at mud depths of 0.05, 0.1, 0.15, 0.25, 0.4, 0.6, 0.9, 1.6 m					

NOTES: Stations and/or depths in *italics* decommissioned early 1998 (see also Table 1).
Depth 3.5 m sensors and stations BO, MM, GW, AD, GC, GE and RW added early 1998.
Locations: +/- 1"; PE, MF, MM +/- 2".
Source: BC Hydro (A. Brotherston, pers. comm., 1997).

Table 3. The first day of each month and the equivalent Julian day relative to January 1, 1995.

Month	Year			
	1995	1996	1997	1998
1-Jan	1	366	732	1097
1-Feb	32	397	763	1128
1-Mar	60	426	791	1156
1-Apr	91	457	822	1187
1-May	121	487	852	1217
1-Jun	152	518	883	1248
1-Jul	182	548	913	1278
1-Aug	213	579	944	1309
1-Sep	244	610	975	1340
1-Oct	274	640	1005	1370
1-Nov	305	671	1036	1401
1-Dec	335	701	1066	1431

Table 4. Summary, cumulative heat energy, summer 1998 (84-day period); and summer 1998 (prorated 27-day period), compared to October 1998 (27-day period).

1	2	3	4	5	6
Heat budget term	**Summer 1998 East of PE** ($x10^3$ GJ)	**Summer 1998 West of PE** ($x10^3$ GJ)	**Summer 1998 Total** ($x10^3$ GJ)	**Summer 1998 average 27 day period** ($x10^3$ GJ)	**October 1998 27 day period** ($x10^3$ GJ)
$Q_{net\ (2)}$	3130	891	4021	1292	-174
Q_{BGS}	4480	0	4480	1440	1900
Q_{water}	279	86	365	117	-368
Q_{tidal}	not calc.	Not calc.	not calc.	not calc.	-1563
$Q_{shallows\ (3)}$	1100	100	1200	386	(note 3)
$Q_{mud\ (4)}$	-140	Not calc.	-140	-45	(note 4)
$Q_{residual\ (1)}$	8291 =tidal? +unexplained[5] + errors	905 =tidal? +unexplained + errors	9196 =tidal? +unexplained + errors	2956 =tidal +unexplained + errors	531 =unexplained + errors

Note 1: $Q_{residual} = Q_{net\ atmospheric} + Q_{sh,mud} + Q_{tidal} + Q_{BGS} - Q_{water}$ (eq. 1)

Note 2: excludes mudflats

Note 3: $Q_{shallows}$ was calculated from the higher temperatures observed in the shallow water overlying the mudflats, compared to shallow water in the main body of PMA. The effect of the shallows in October is expected to be small and probably negative, representing lower water temperatures overlying mudflats due to cooler mud temperatures when exposed (Fissel et al. 1998).

Note 4: Q_{mud} is the heat captured by the mud from the water and from direct solar radiation upon the mudflats, and sequestered over the summer at depth within the mudflats (Fissel et al. 1998). Following the summer, this seabed heat is slowly released to the water (Fissel et al. 1998).

Note 5: "unexplained" is that portion of the residual outside of errors that may represent smaller processes that have not been accounted for.

Table 5. Summary of heat transport by water currents, compared to the same quantities using predicted currents (October 1-27, 1998).

Layer (depth)	$Q_{observed}$ ($x10^3$ GJ)	$Q_{predicted}$ ($x10^3$ GJ)	$Q_{pred.minus\ mean}$ ($x10^3$ GJ)
1 *(0 to 6.5 m)*	-3333	-3174	-3250
2 *(6.5 to 10 m)*	1008	1010	954
3 *(10 to 13.5 m)*	391	388	291
4 *(13.5 to 18 m)*	262	246	164
5 *(18 to 22.5 m)*	85	75	59
6 *(18 m to seabed)*	23	17	16
Cumulative 1+2+3+4+5+6	-1563	-1438	-1762

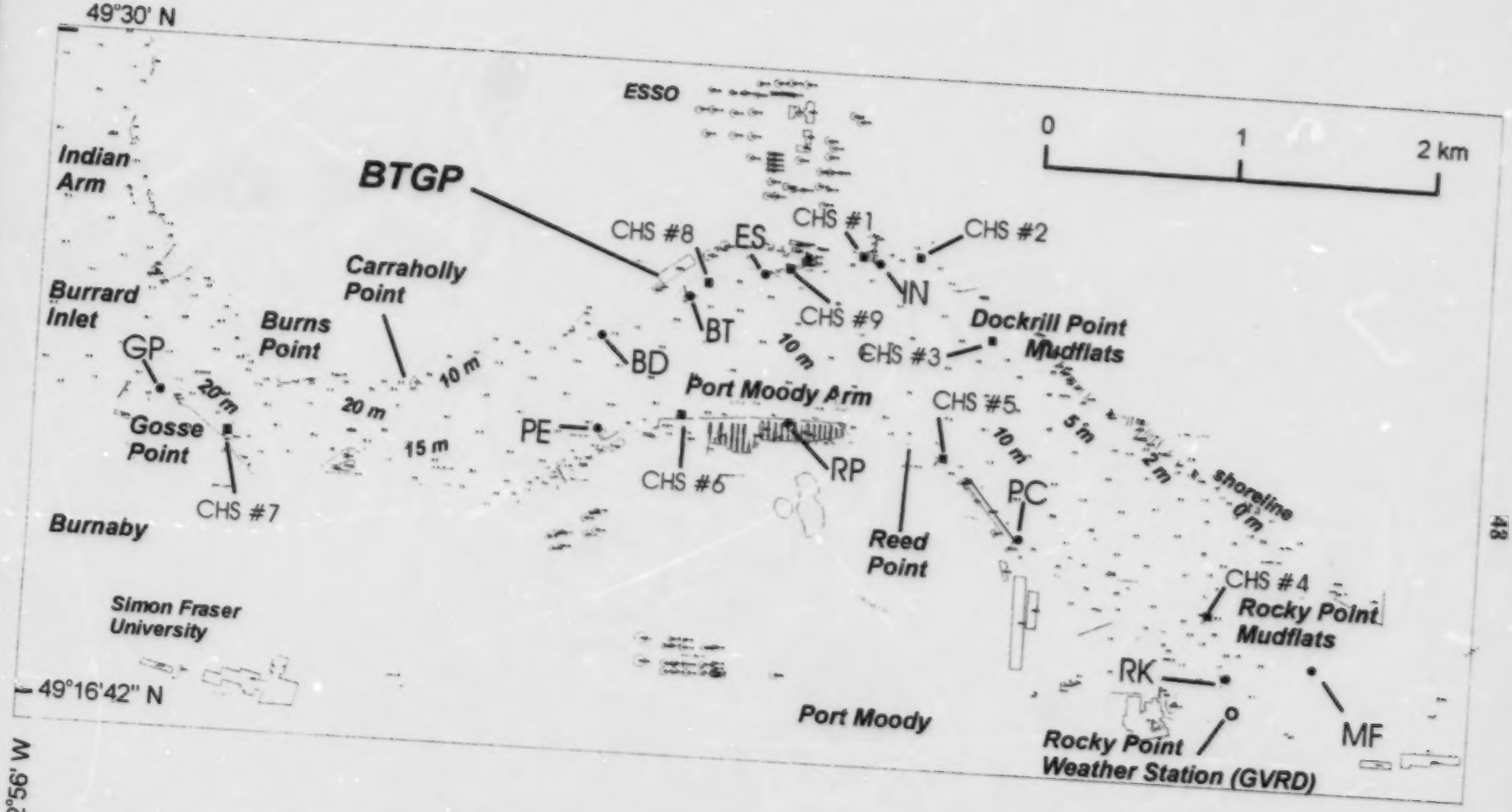


Figure 1. Port Moody Arm and environs. Location of water temperature measurement sites (BD, BT etc. operated by BTGP; CHS#1, etc. operated by Centennial High School). Depths are in metres and reduced to Chart Datum (3.1 m below Mean Water Level). From Canadian Hydrographic Service (1992), Chart 3495 .

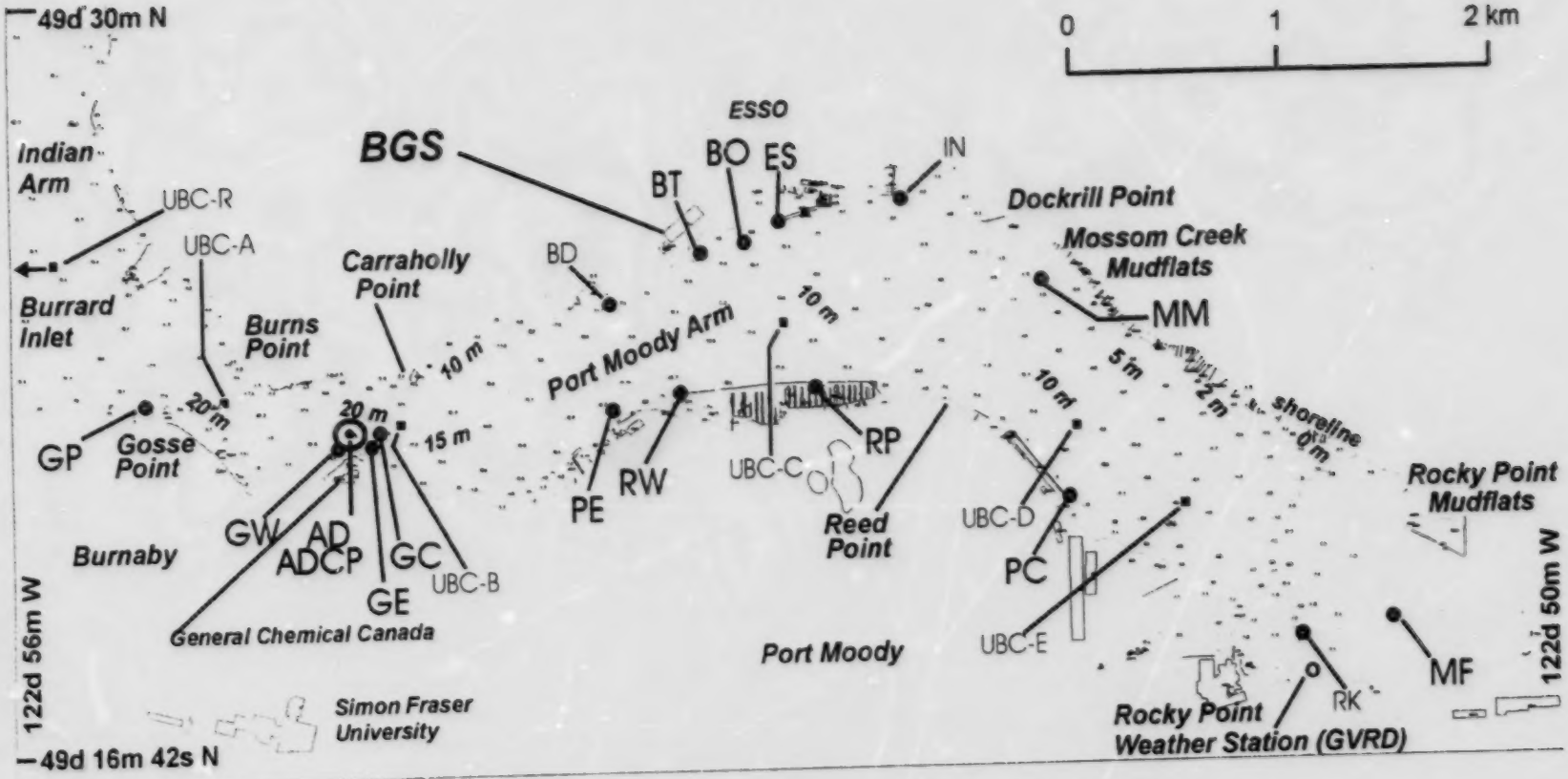


Figure 2. Port Moody Arm and environs. Location of Burrard Generating Station (BGS) and water temperature measurement stations:

BD, BT, ...: operated by BC Hydro (various times after August 1995);
UBC-x, ...: profiling stations operated by UBC (Summer 1998-);
ADCP: Acoustic Doppler Current Profiler station (October 1998)

Depths on map are in metres reduced to Chart Datum (3.1 m below mean water level).
Based on Canadian Hydrographic Service (1992), chart 3495.

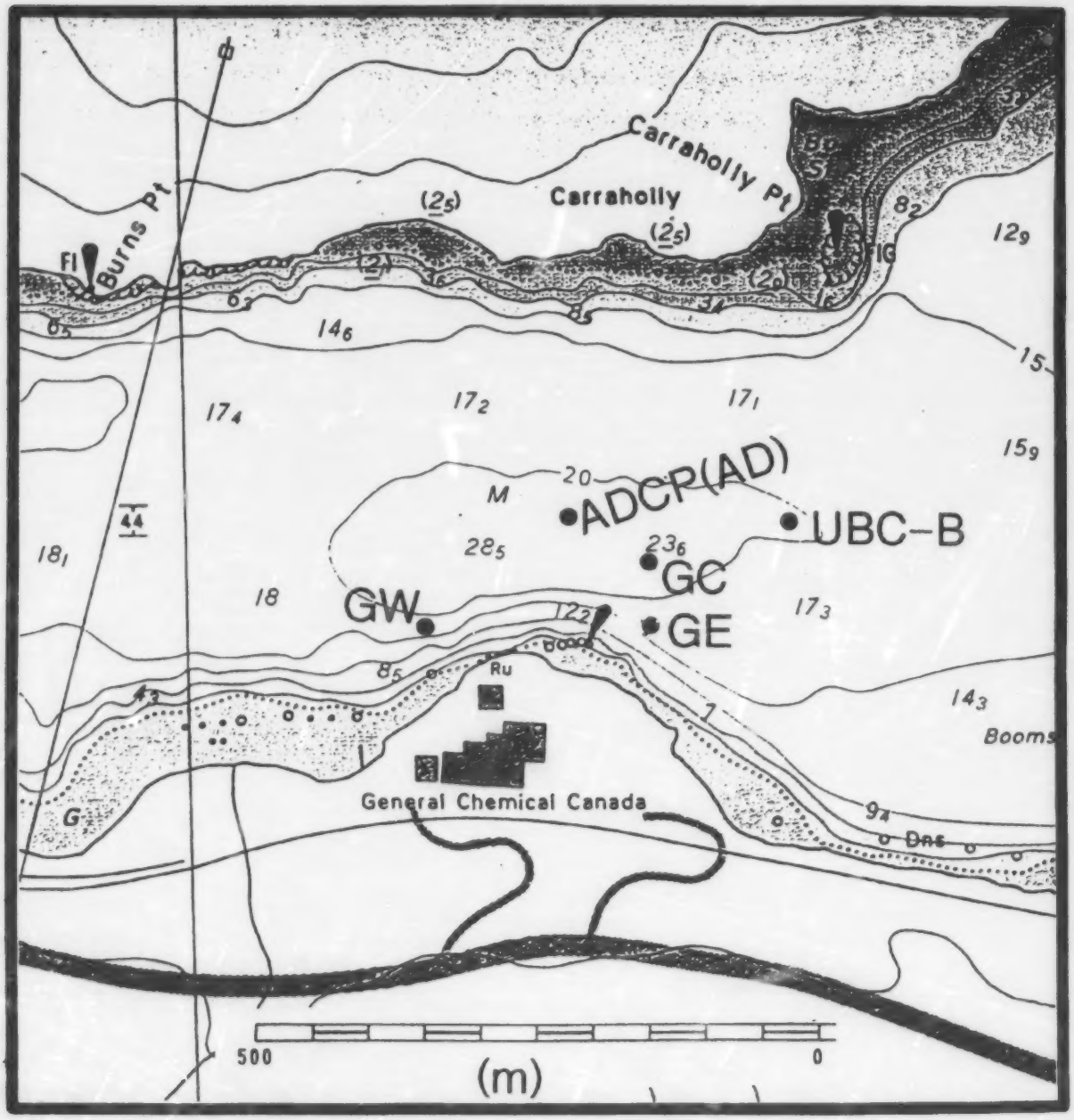


Figure 3. Station locations in the vicinity of the ADCP unit. Water depths (m) are relative to chart datum; mean water level is 3.1 m greater. Contours are at 2 m, 5 m, 10 m, 15 m and 20 m. Scale in metres. Based on Canadian Hydrographic Service (1992), Chart 3495.

Figure 4. The Acoustic Doppler Current Profiler (ADCP) as installed southwest of Carraholly Point, October 1998

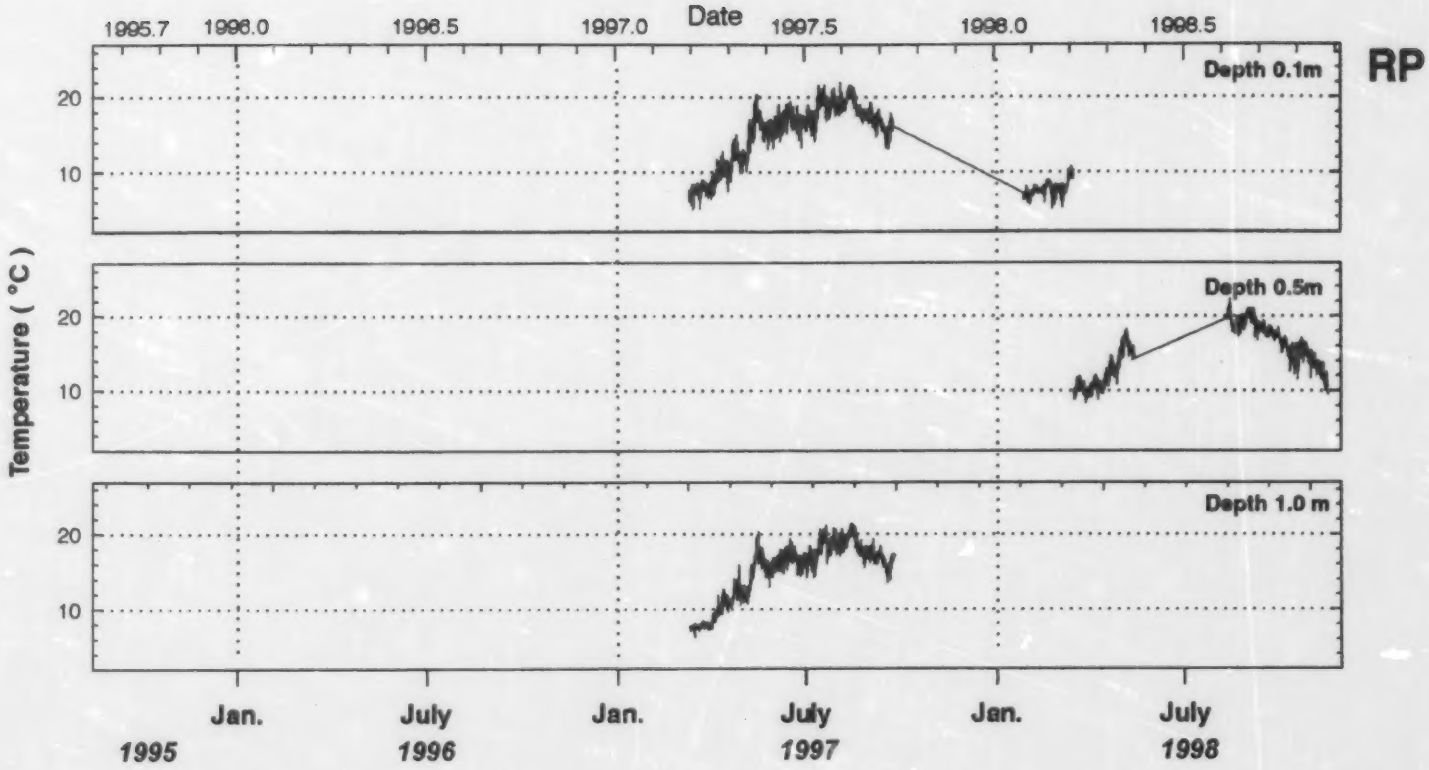


Figure 5a. Water temperature time-series data at station RP, Reed Point, from August 1995 to October 1998, at depths indicated.

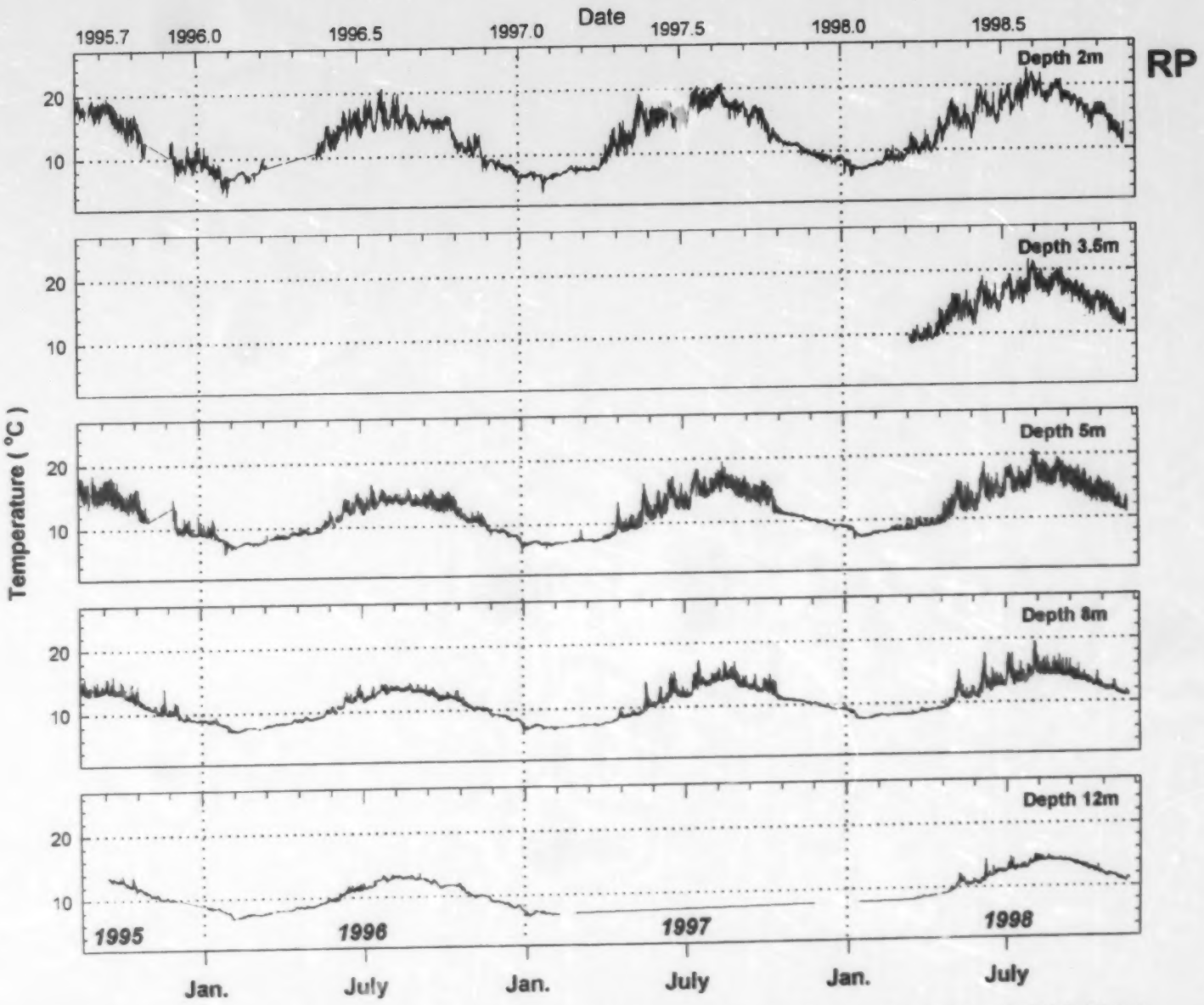


Figure 5b. Water temperature time-series at station RP, Reed Point, from August 1995 to October 1998, at depths indicated.

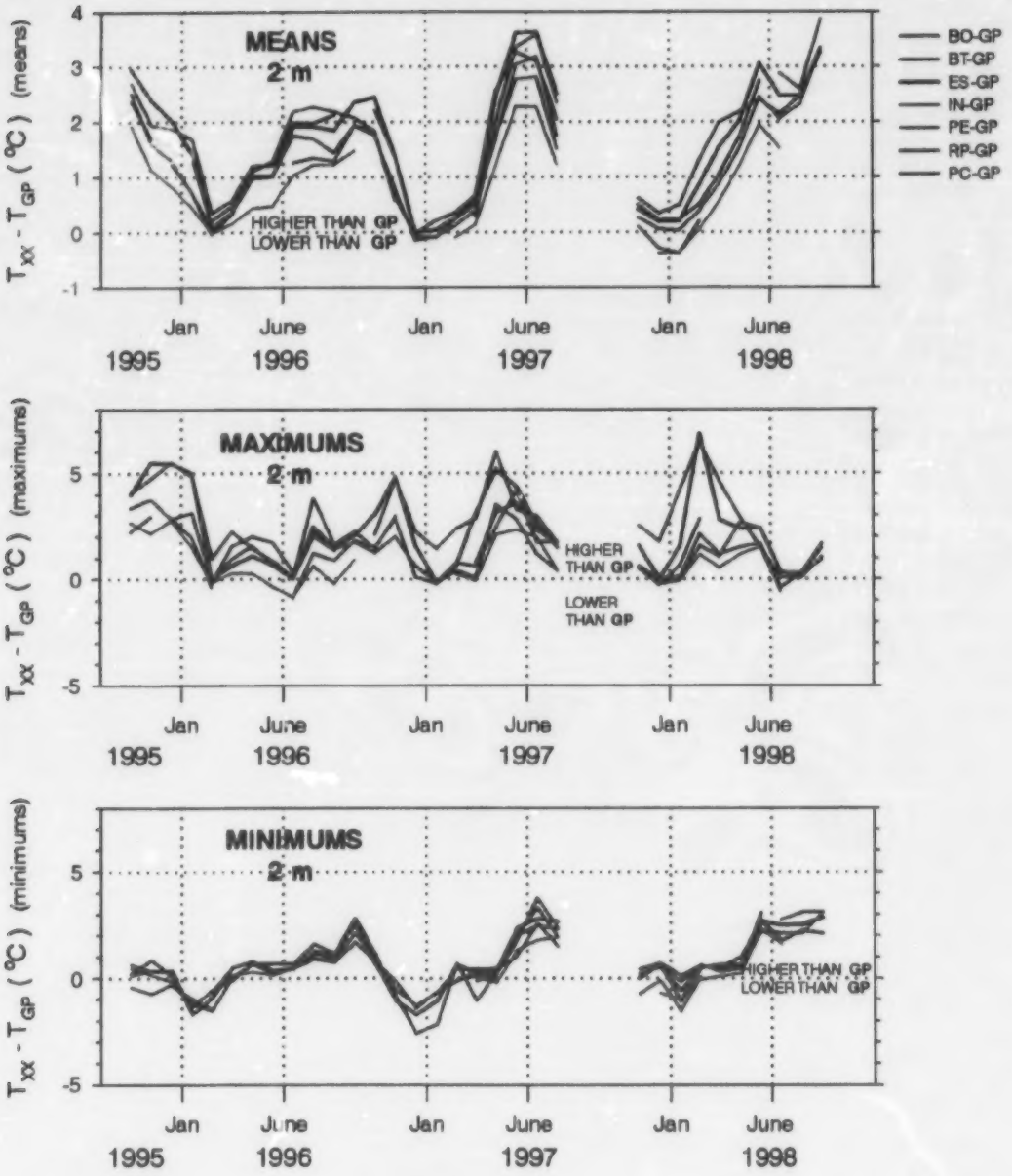


Figure 6. Difference of the monthly mean, maximum and minimum temperatures at a depth of 2 m in Port Moody Arm from those at Station GP (Gosse Point), for 1995-1998.

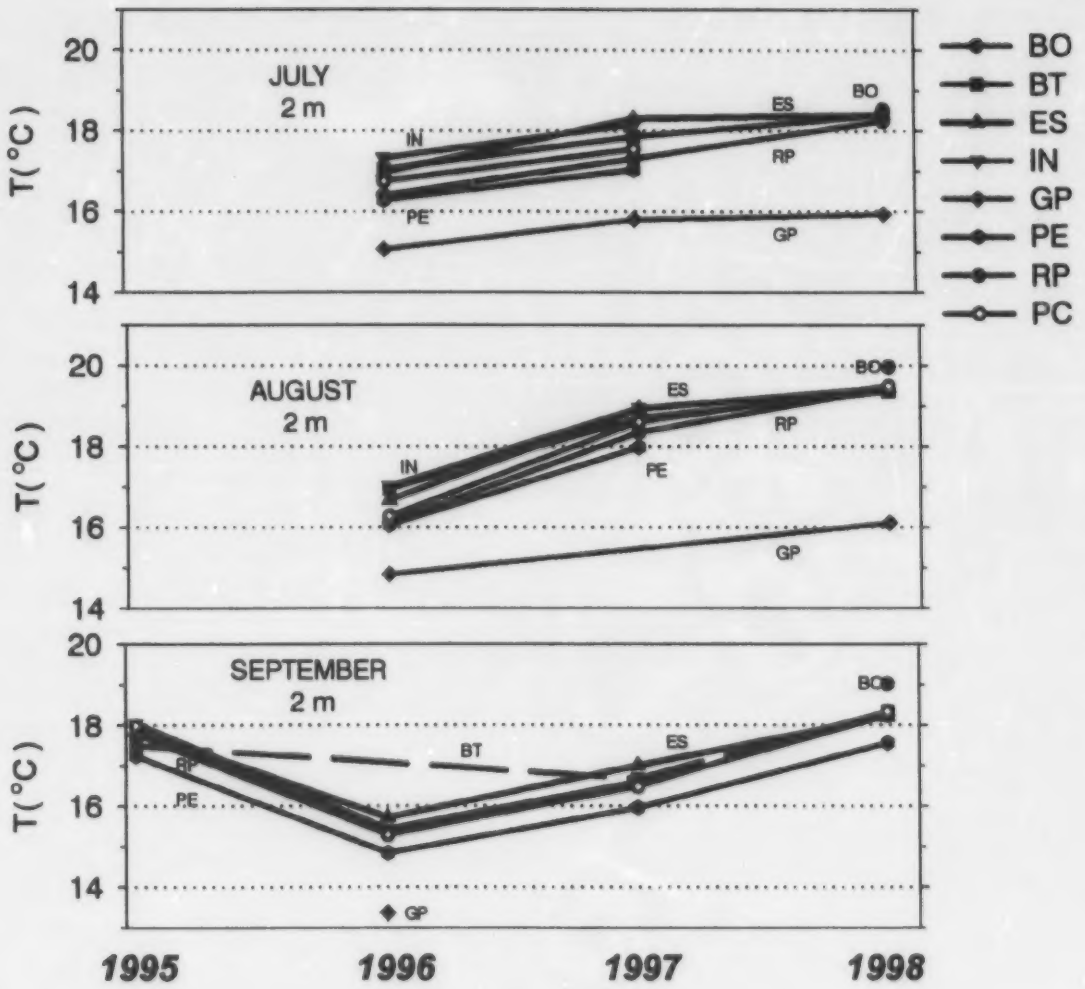


Figure 7. Year-to-year changes in monthly mean water temperatures at a depth of 2 m in Port Moody Arm for the summer months, 1995-1998.

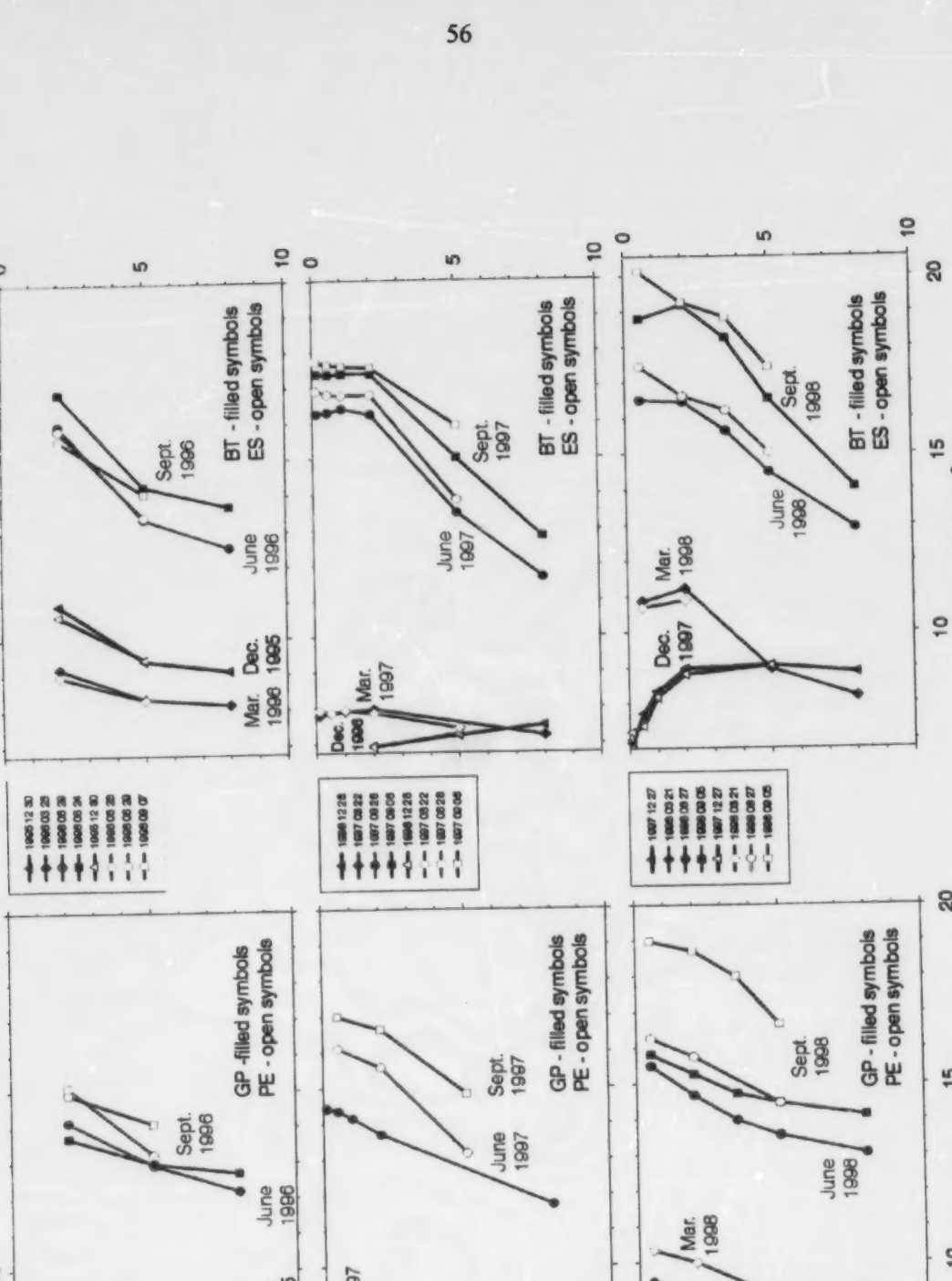


Figure 8a. Plots of seasonal 14-day mean water temperature profiles (to 8 m depth) in Port Moody Arm for pairs of measurement stations in the western Arm (GP, PE) and in the eastern Arm (BT, ES).

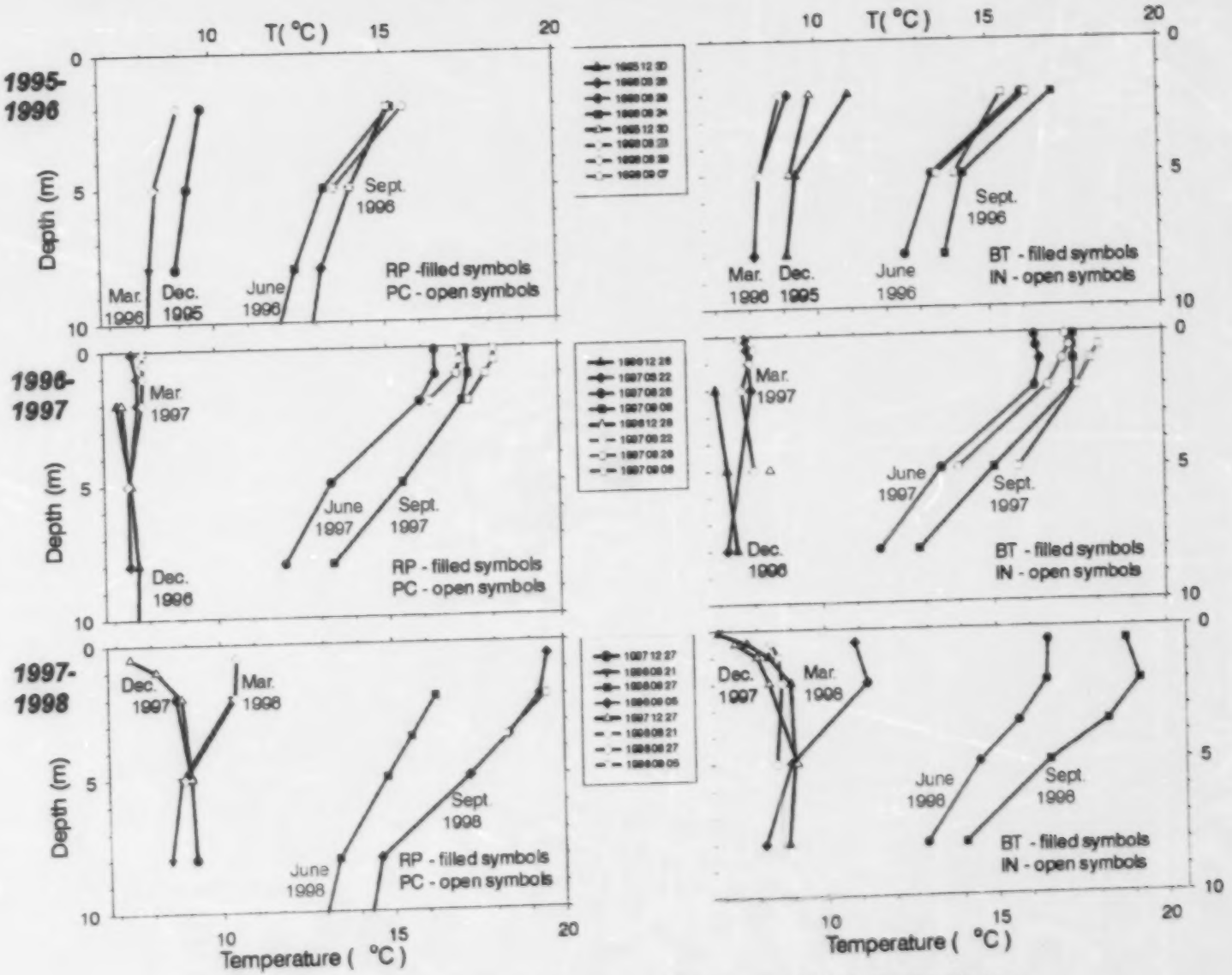
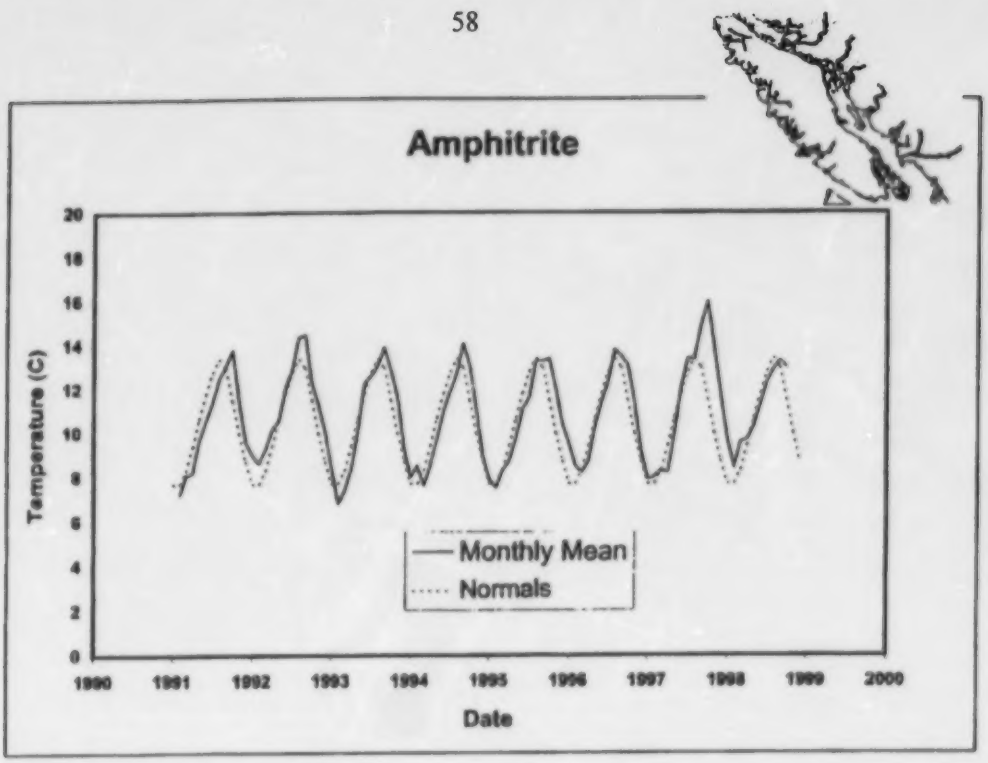


Figure 8b. Plots of seasonal 14-day mean water temperature profiles (to 8 m depth) in Port Moody Arm for pairs of measurements in the northern and southern areas of the eastern Arm.



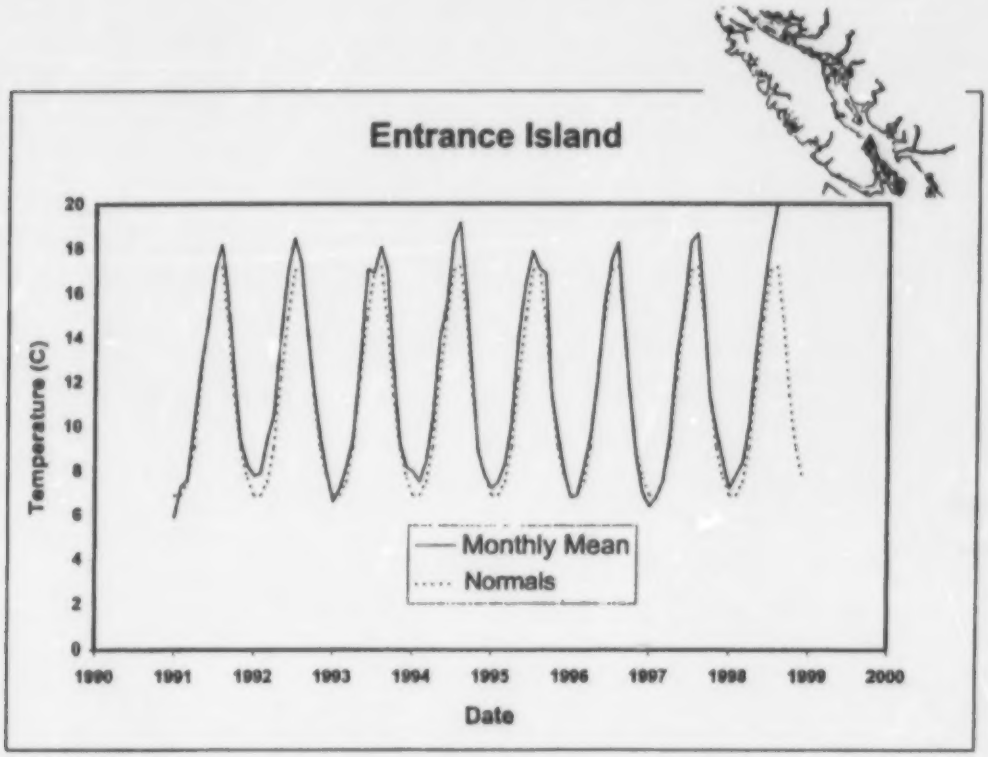


Figure 9. Monthly mean ocean surface temperatures measured from 1990 to 1998 at Amphitrite Point on the Pacific Coast of Vancouver Island and at Entrance Island in the Strait of Georgia, versus monthly mean ocean surface temperature "normals".

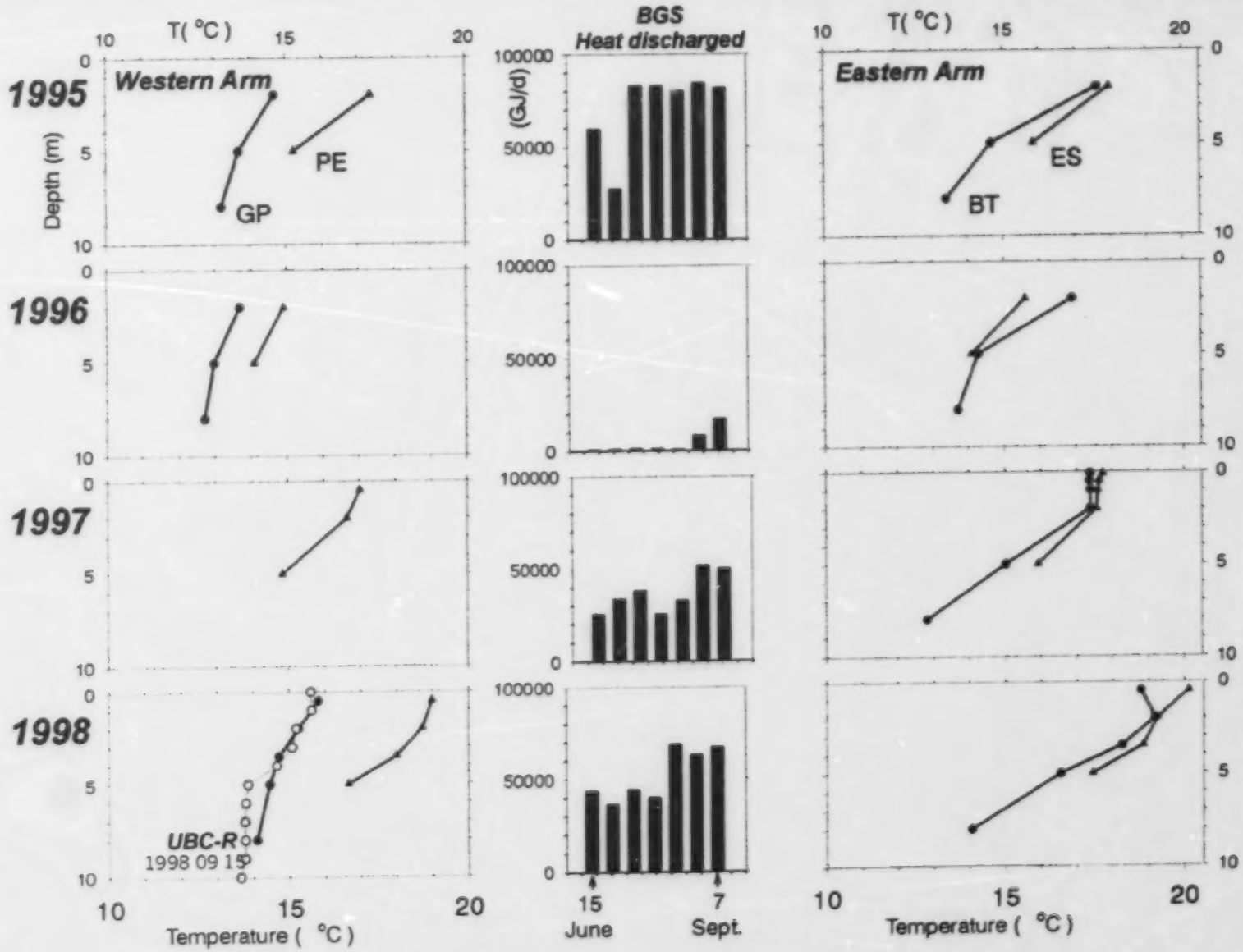


Figure 10. Plots of early September 14-day mean water temperature profiles (to 8 m depth) in Port Moody Arm for years 1995 to 1998, and variation of heat discharged by BGS over summer of the same years.

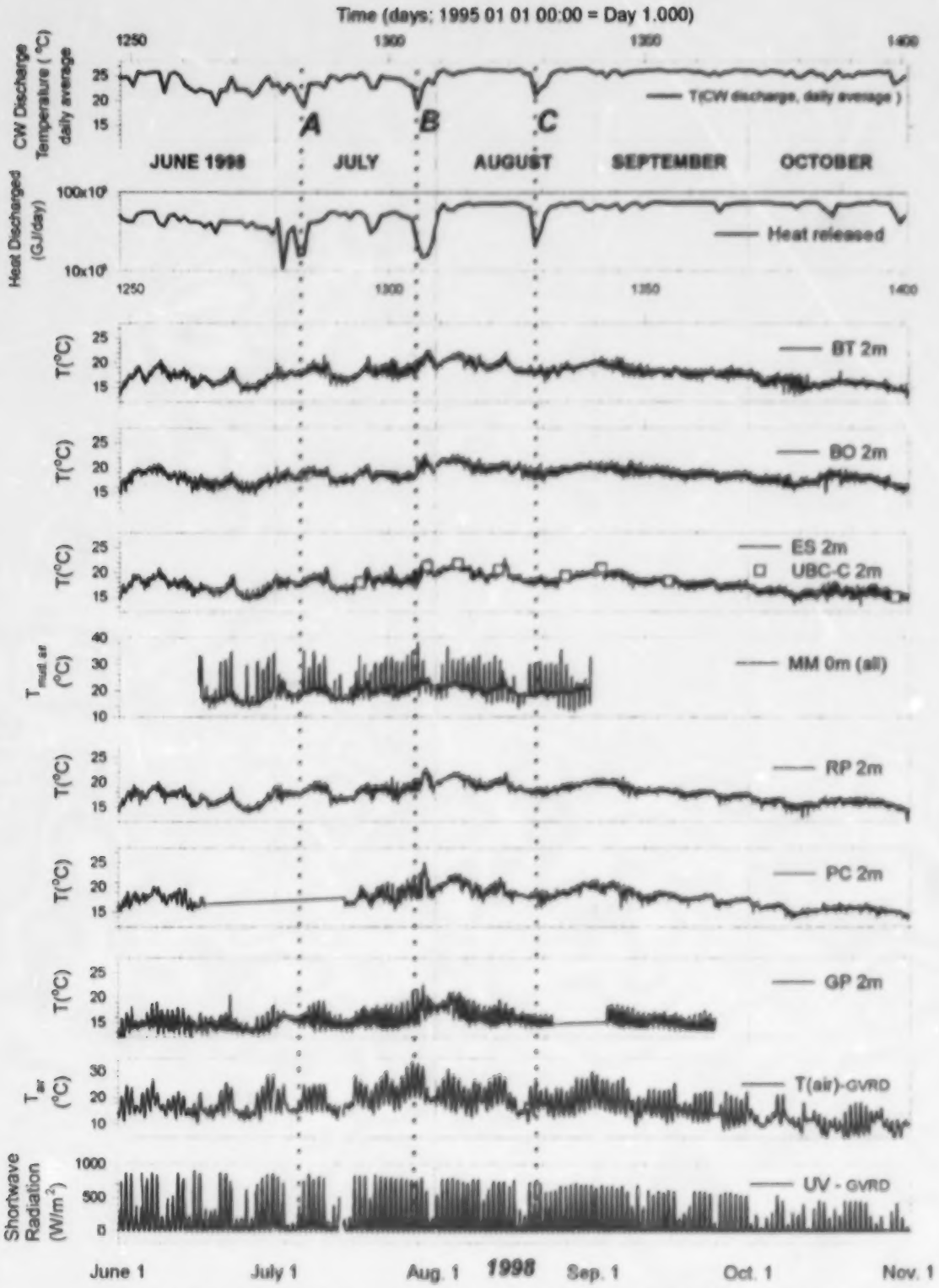


Figure 11. Summary of Burrard Generating Station operational parameters, water temperatures and meteorological parameters, June 1 to November 1, 1998.

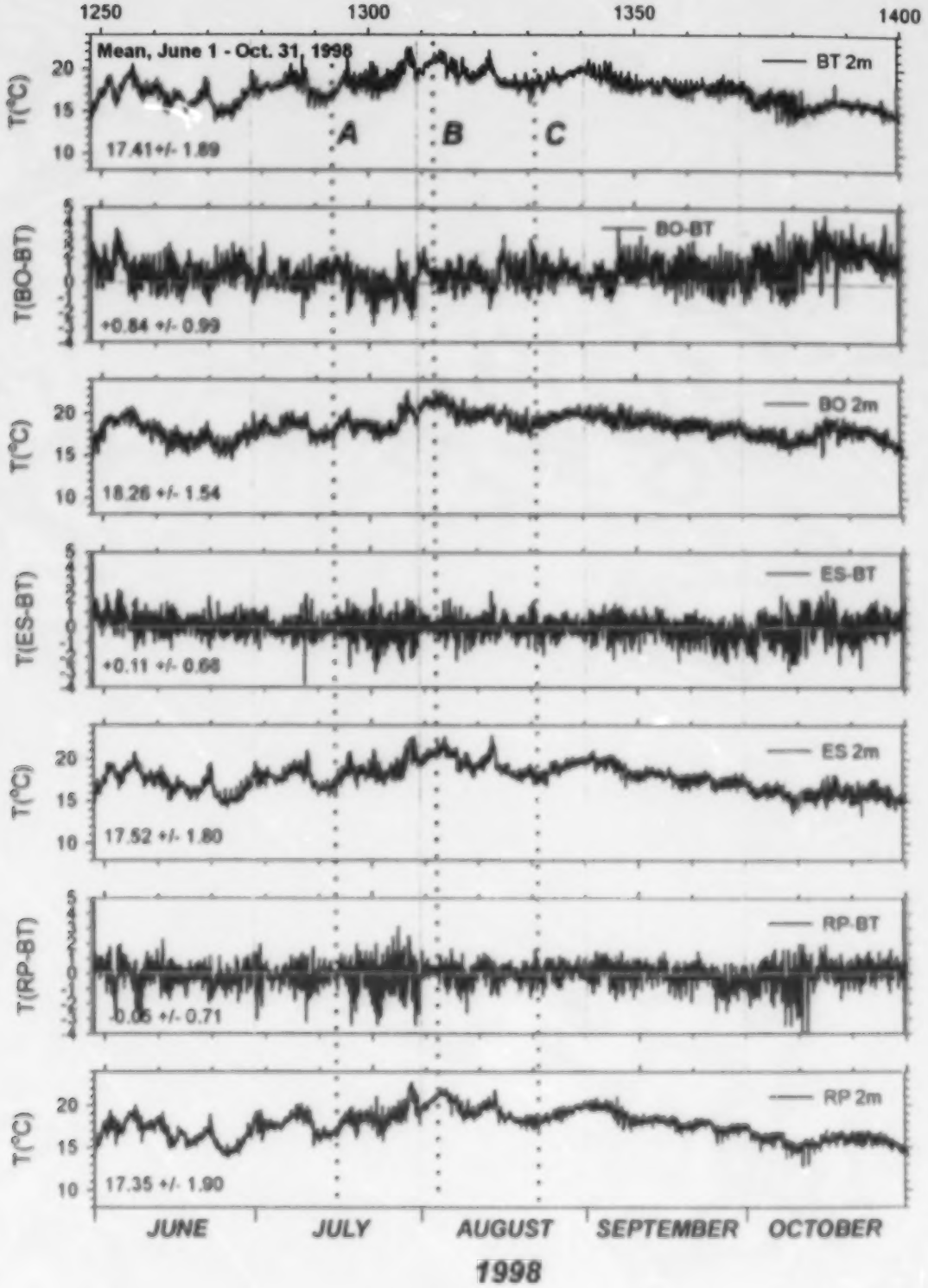


Figure 12. Water temperatures at depth of 2 m for stations in the vicinity of the Burrard Generating Station, and the temperature differences from Station BT, during summer and fall, 1998. Mean +/- standard deviation shown for period June 1- October 31, 1998.

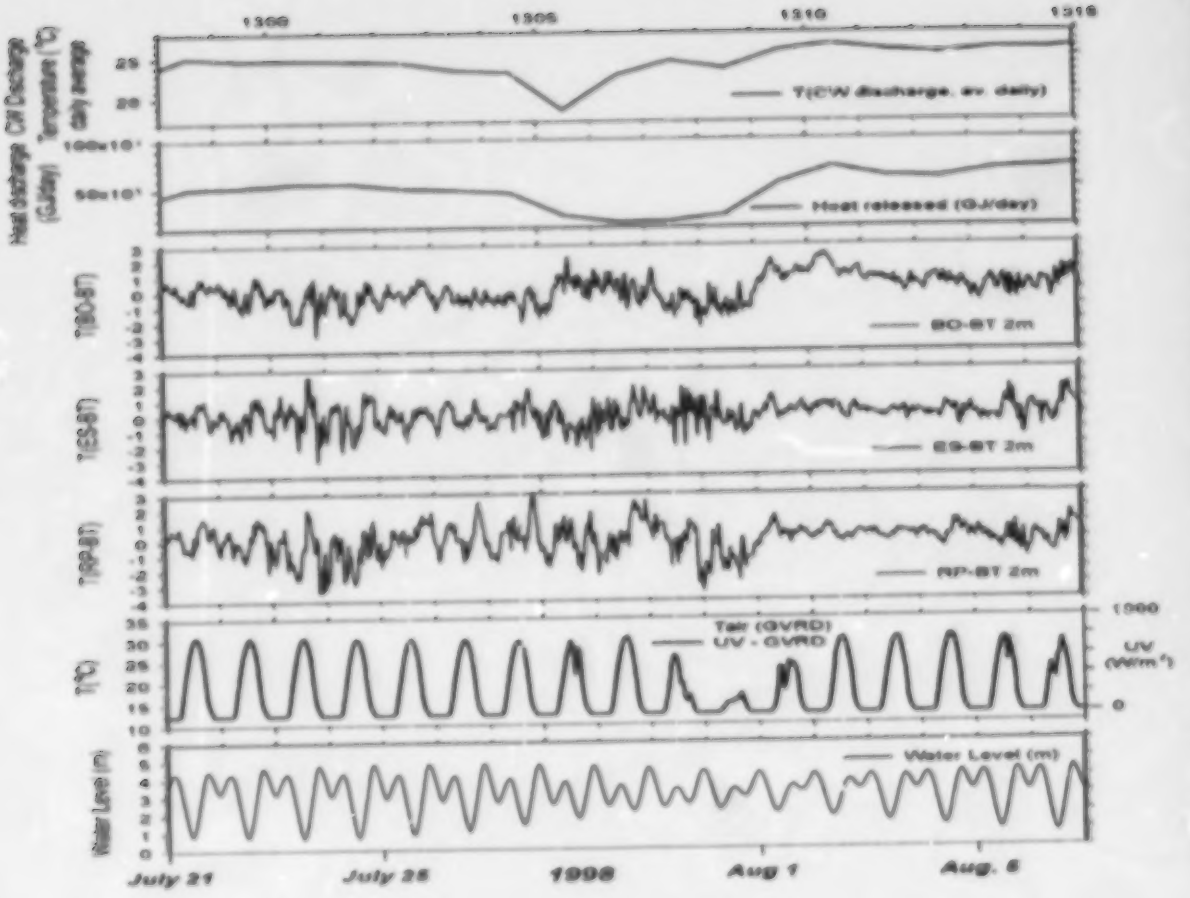


Figure 13. Burrard Generating Station operational parameters and temperature differences of several stations from Station BT, together with meteorological parameters during July and August 1998

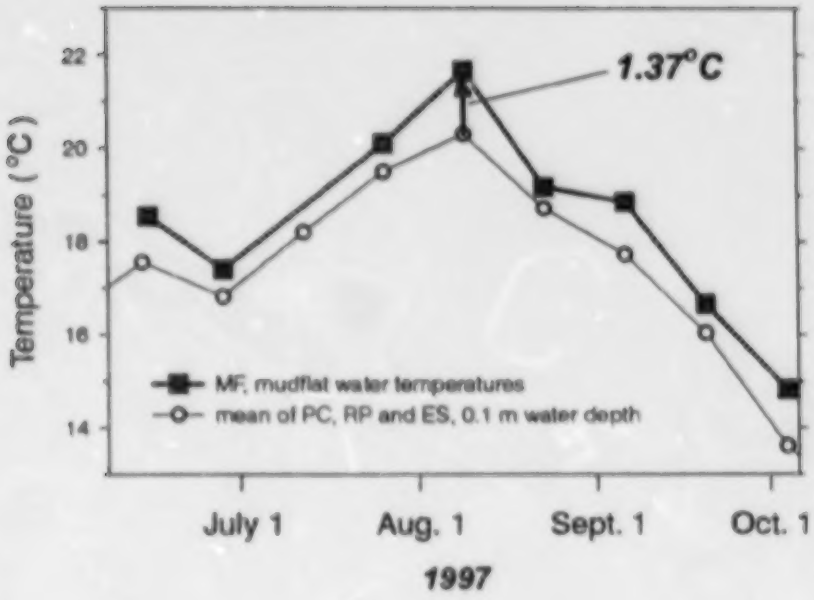


Figure 14. Temperatures of water in the tidal prism overlying the Rocky Point mudflat, compared to nearby sea surface temperatures in non-mudflat areas (summer 1997, based on 14-day means).

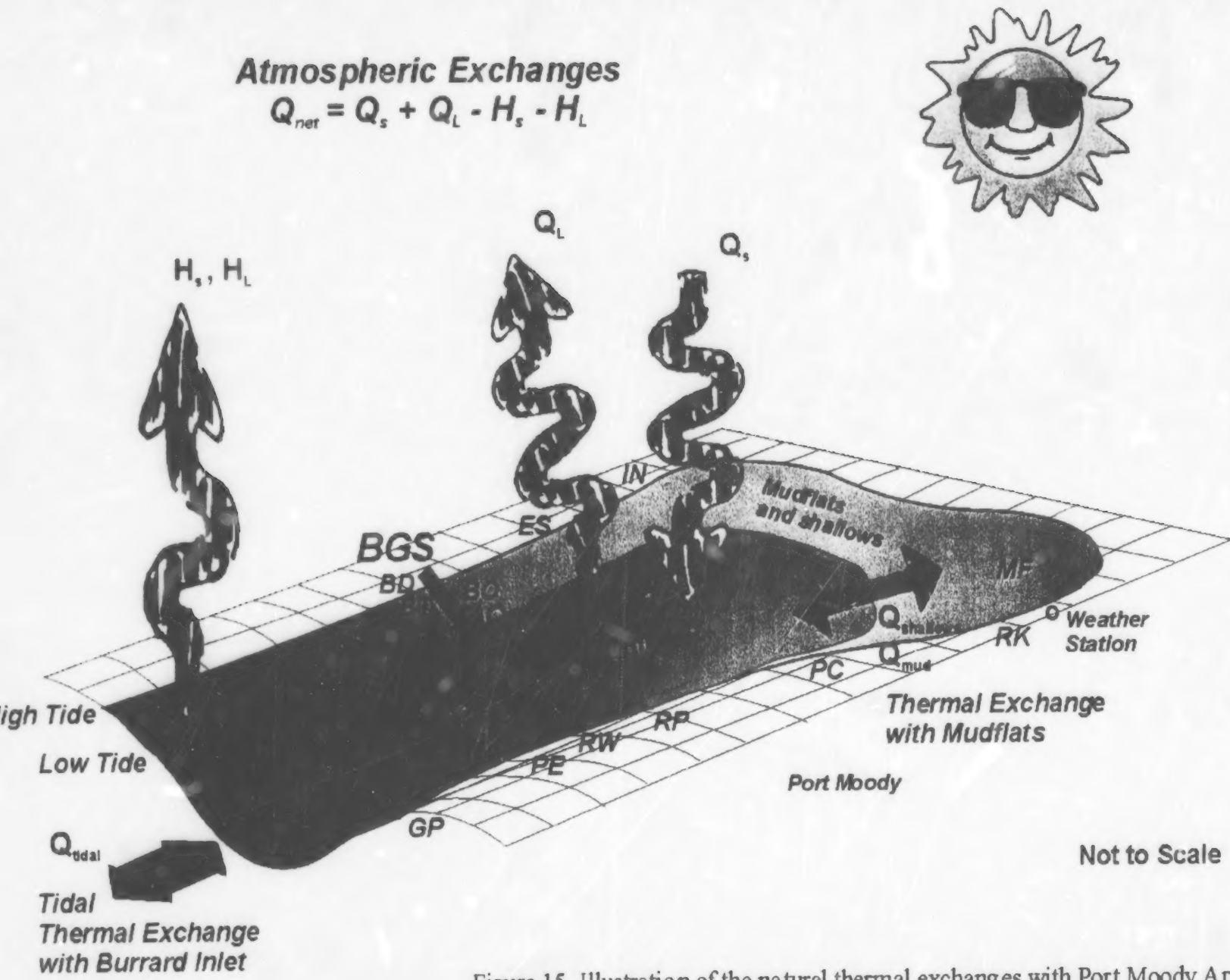


Figure 15. Illustration of the natural thermal exchanges with Port Moody Arm and the heat discharged by the Burrard Generating Station

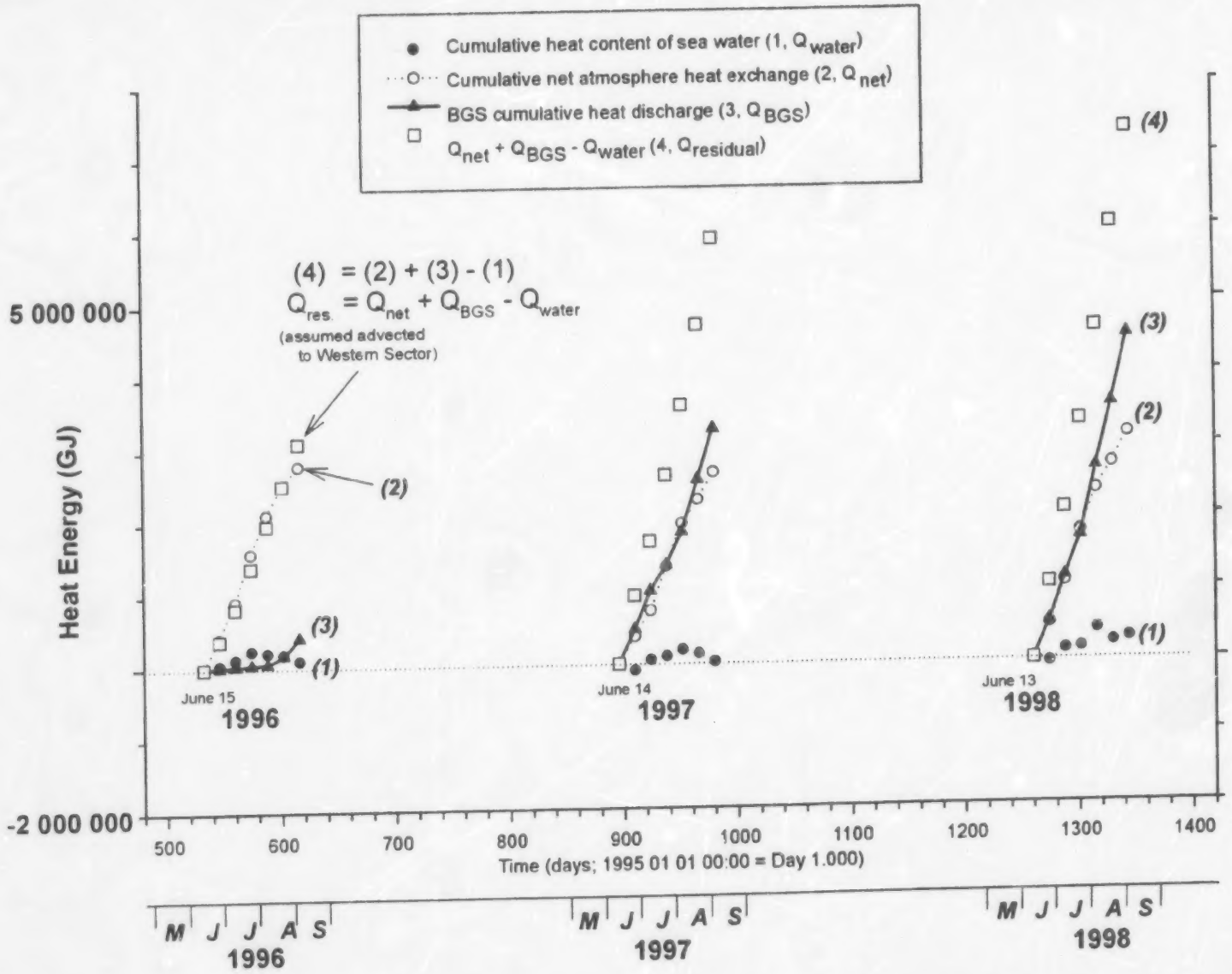


Figure 16. Components of the summer heat budget analysis, 1996-1998, area of main body of Port Moody Arm, Stations PE, BT and east.

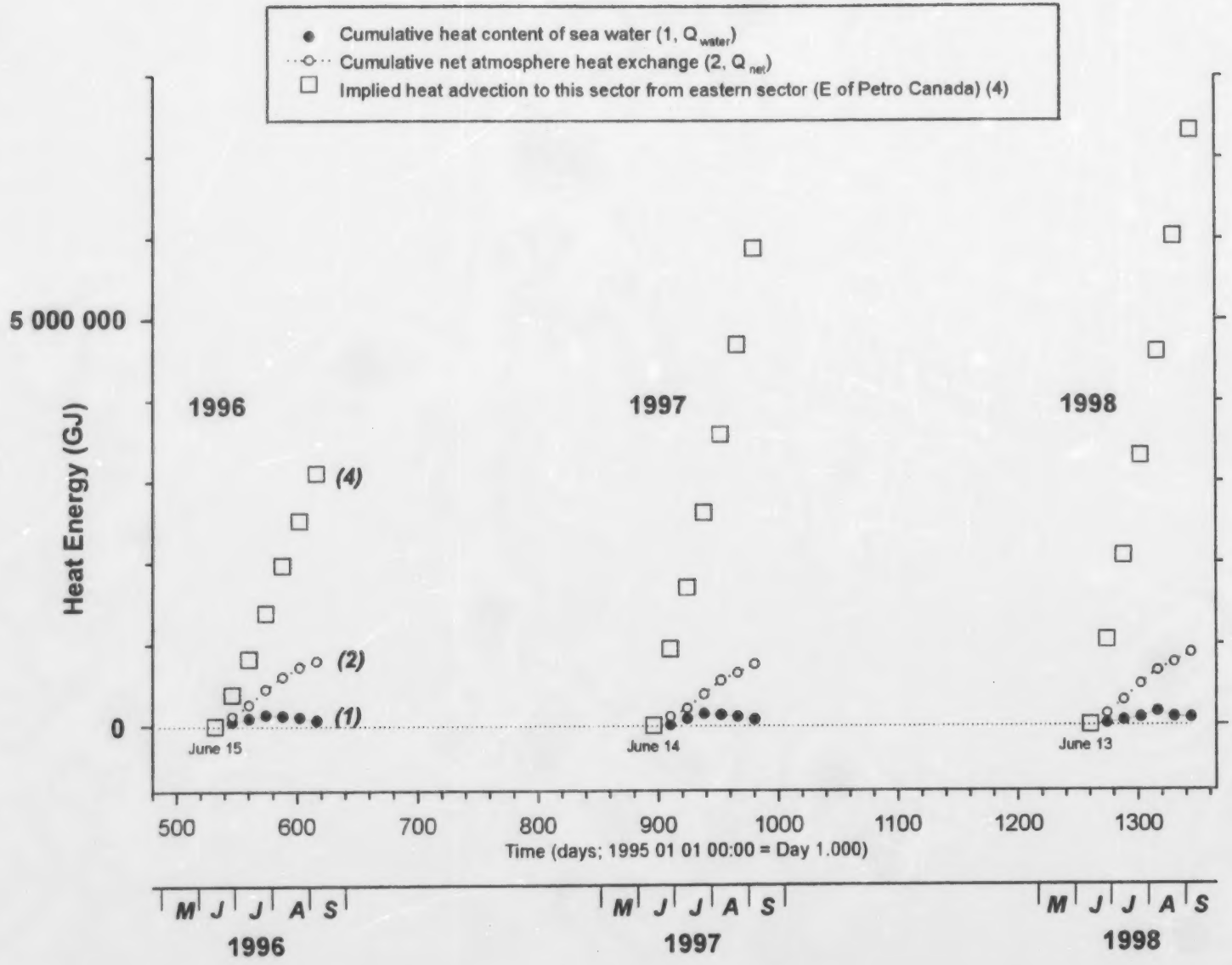


Figure 17. Components of the summer heat budget analysis, 1996-1998, area of Station GP at outlet of Port Moody Arm.

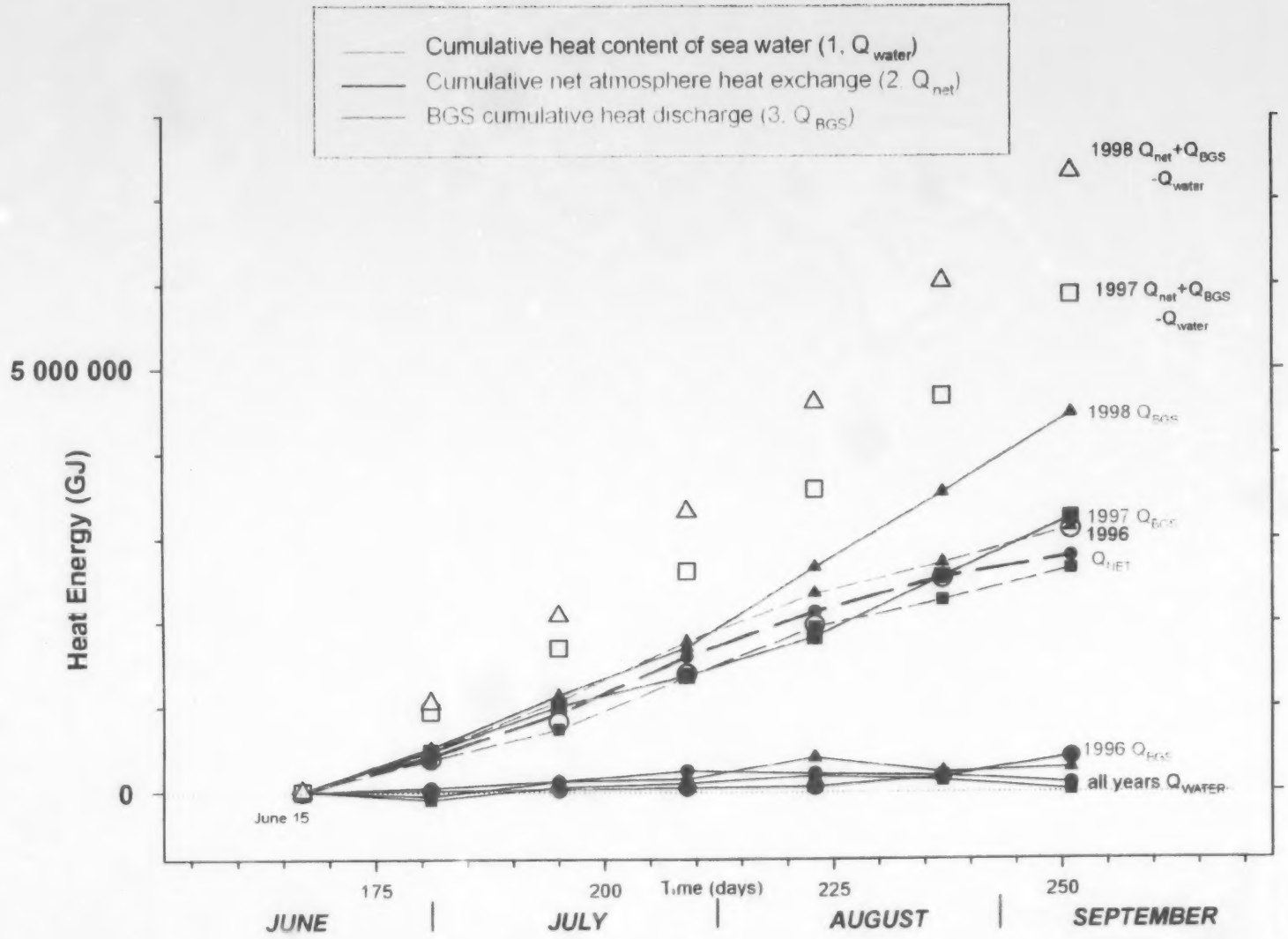


Figure 18. Comparison of 1996, 1997 and 1998 summer heat budget components for the main body of Port Moody Arm, Stations PE, BT and east, plotted on a common month scale.

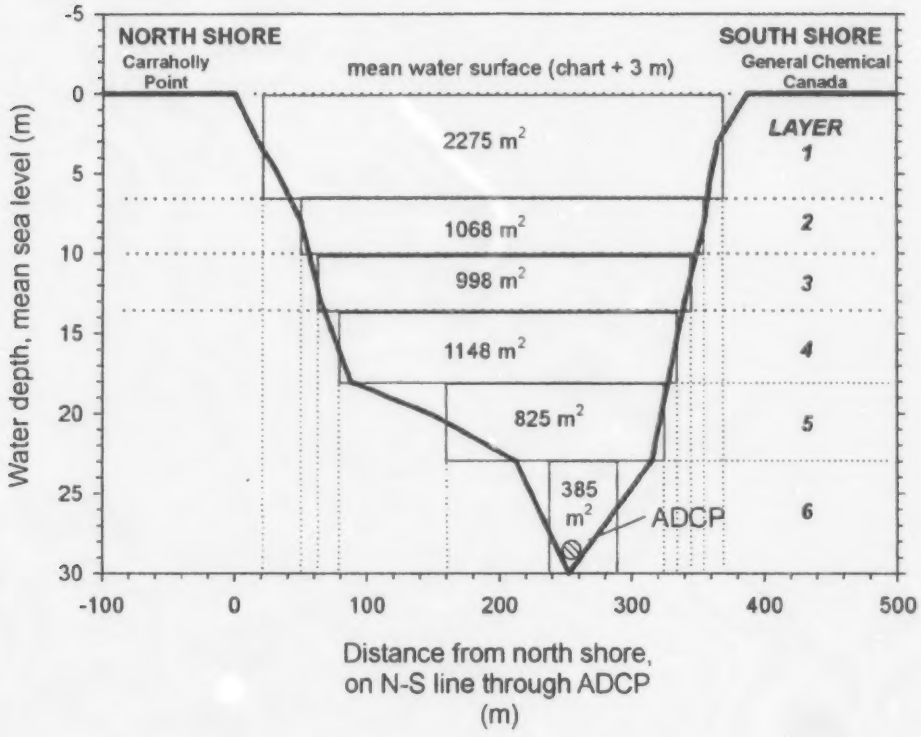


Figure 19. Channel cross-section, Port Moody Arm, Carraholly Point to General Chemical Canada plant through ADCP location. The cross-section was subdivided into six layers for use in the current/tidal heat transport analysis. Cross-sectional areas of each layer are given.

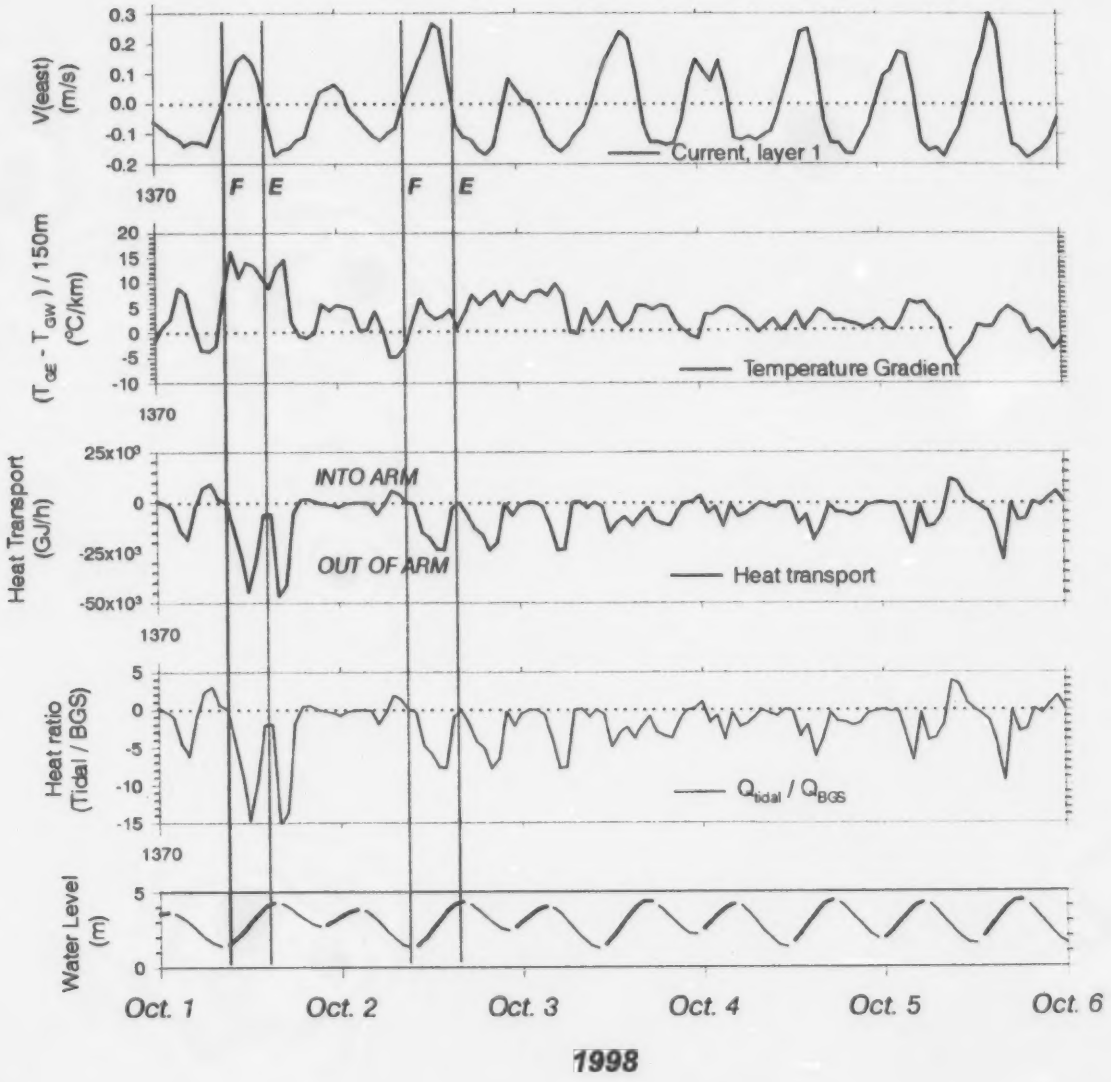


Figure 20. Tidal currents and temperature gradients used in the calculation of tidal heat transport for the upper layer (0 to 6.5 m) in the channel between Carraholly Point and the General Chemical Canada plant, October 1-5, 1998.

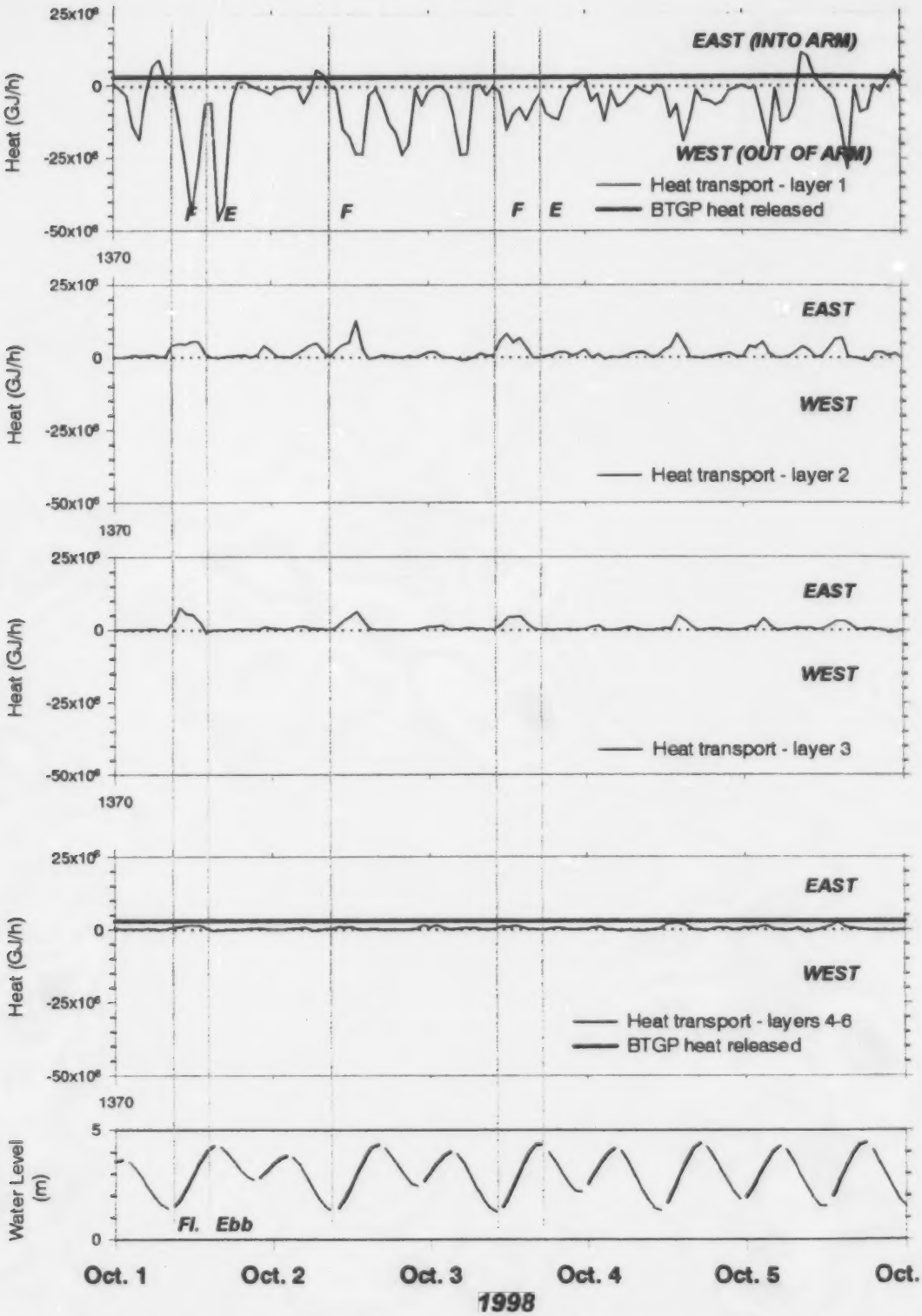


Figure 21. Tidal heat transport in channel between Carraholly Point and General Chemical Canada plant, October 105, 1998, for each layer shown in Figure 19.

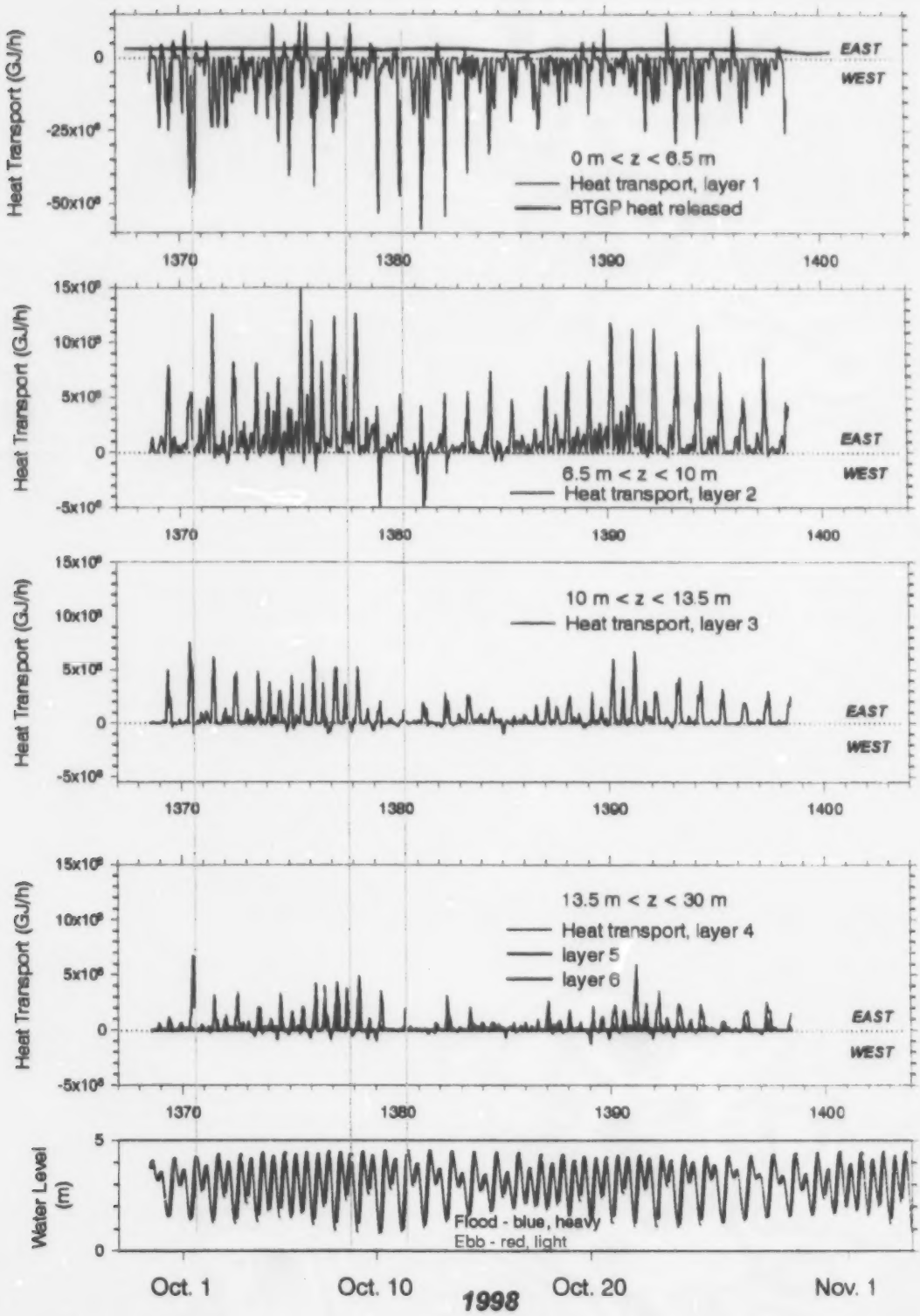


Figure 22. Tidal heat transport in channel between Carraholly Point and General Chemical Canada plant, September 29 - October 29, 1998, for layers of Figure 19.

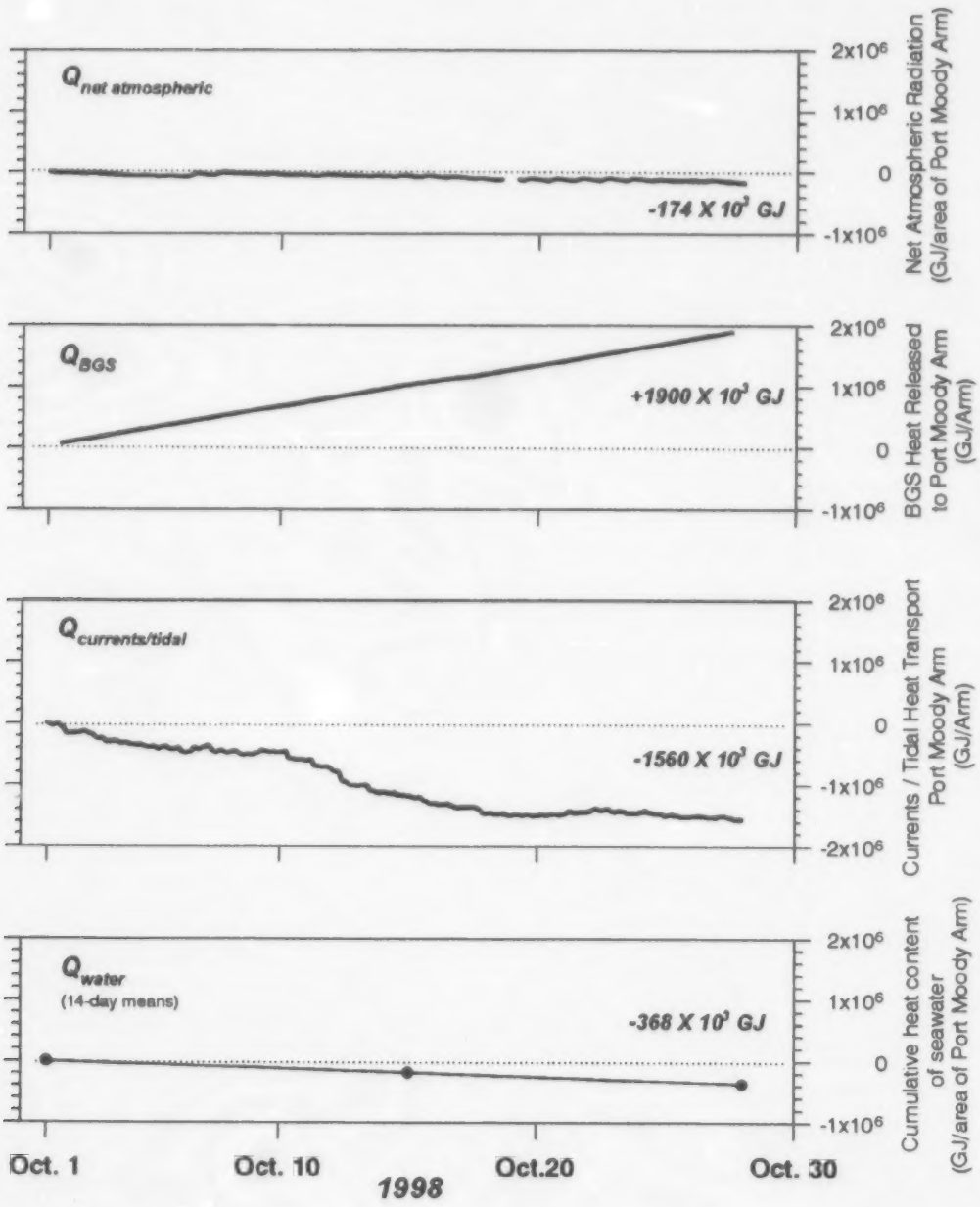


Figure 23. Components of the cumulative heat budget calculation for Port Moody Arm, October 1-27, 1998. Cumulative heat budget values attained by the end of this period are given in bold italics on each plot.

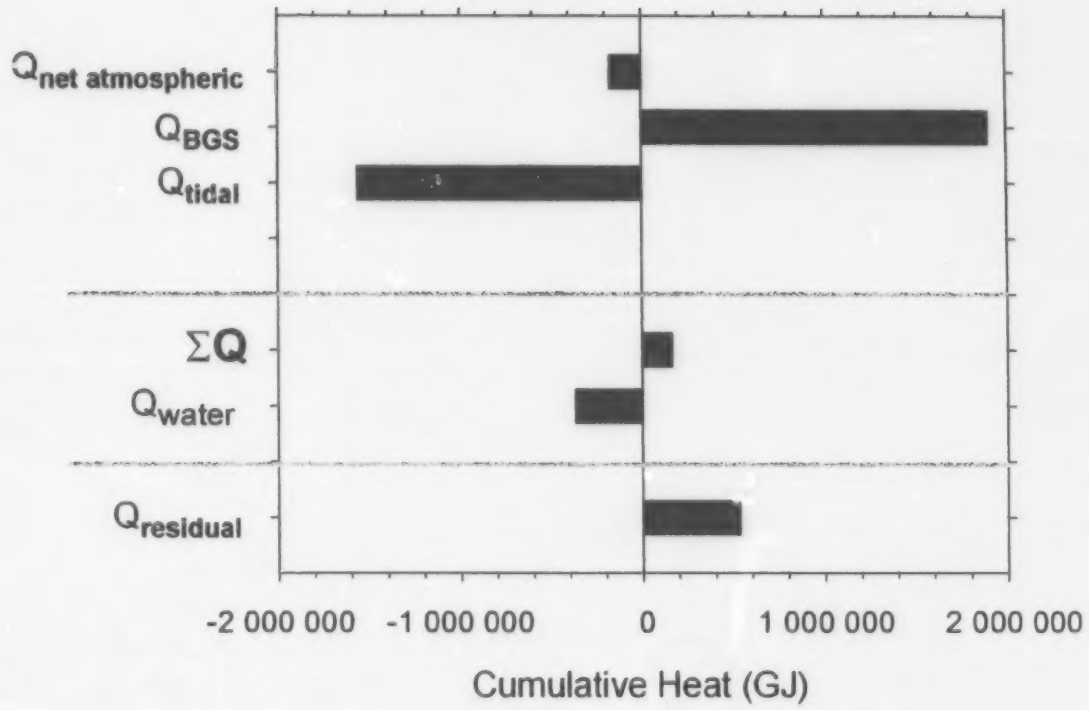


Figure 24. Summary of cumulative heat gains and losses for Port Moody Arm, October 1-27, 1998.

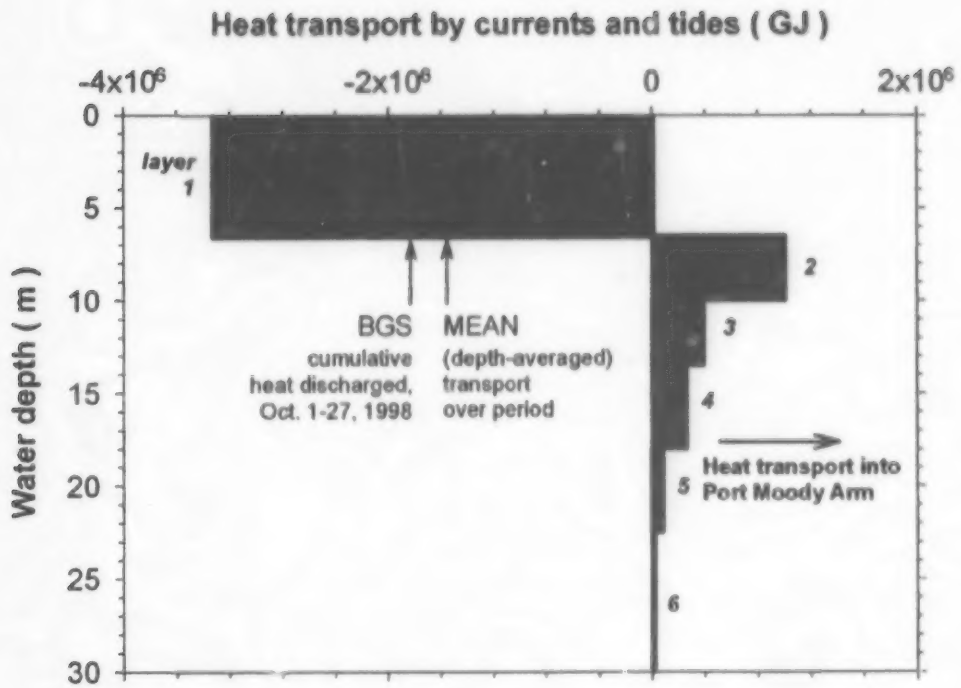


Figure 25. Cumulative heat carried into or out of Port Moody Arm by currents and tides, versus water depth, for the period Oct. 1-27, 1998.

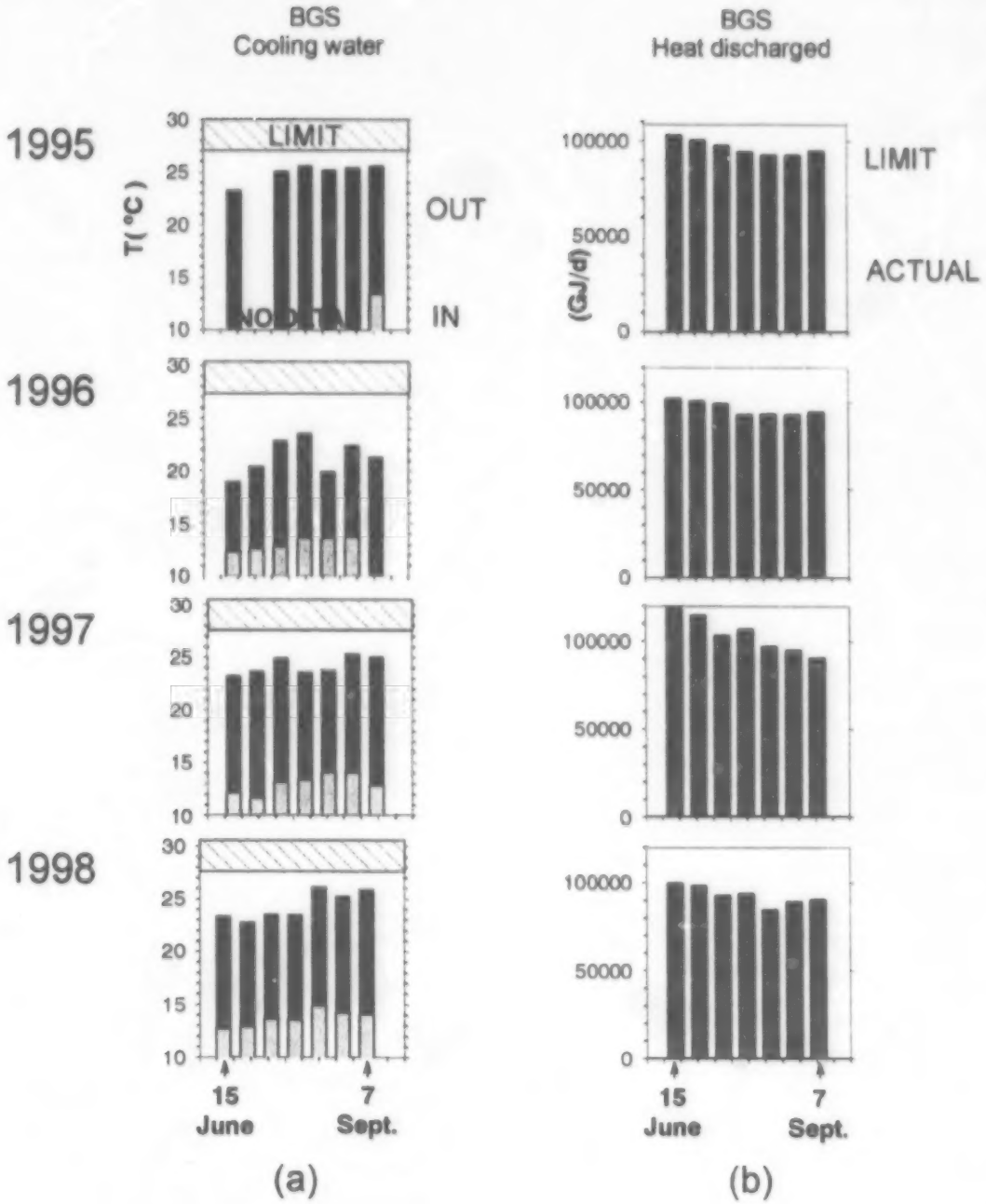


Figure 26. Summary of summer BGS operational data on a 14-day mean basis for the years 1995 to 1998
(a) Cooling water temperatures at intakes (IN) and at discharge (OUT);
(b) Heat discharged by the BGS (ACTUAL) and the calculated maximum heat that is possible to discharge within the present operating license conditions of temperature and cooling water flow rate.

APPENDIX A: MONTHLY WATER TEMPERATURE CONTOUR MAPS OF PORT MOODY ARM

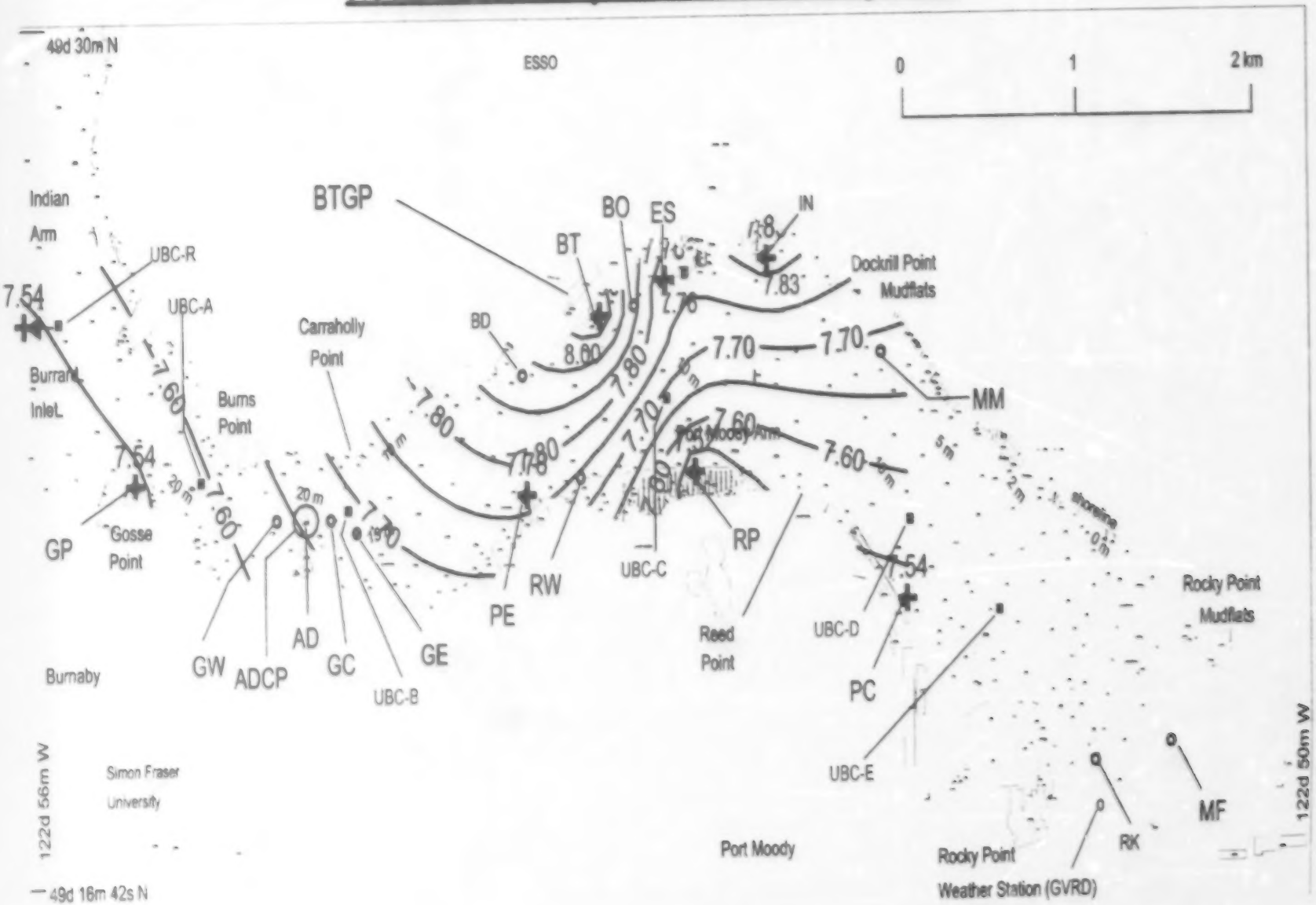
Monthly mean water temperatures at 0.5 m, 2 m and 5 m depth have been used to create water temperature contour maps of PMA, for the period February to September, 1998 and for October 29, 1998. The maps are based on the BC Hydro data set (Tables 1, 2), augmented by temperature-depth profile measurements taken occasionally at 6 locations throughout the arm (UBC data; Taylor et al. 1999). Golden Software's ***Surfer™*** program was used to create the maps; see below for a description of the method used. Note that the relatively sparseness of the available data has necessitated considerable interpolation and extrapolation: users should be aware of these limitations to accuracy.

Maps: All present and decommissioned stations are labeled, and those contributing data to the particular map are indicated by bold "+" (Station UBC-R is actually located somewhat west of the map boundary, but for this purpose has been sited at the western edge of the map). Water temperatures are contoured generally at 0.1°C intervals and a gray-scale shading is used on some maps to accent the trends (the same scale is used for all months).

For further details on preparation of these maps, see Appendix E.1, Taylor et al. 1999.

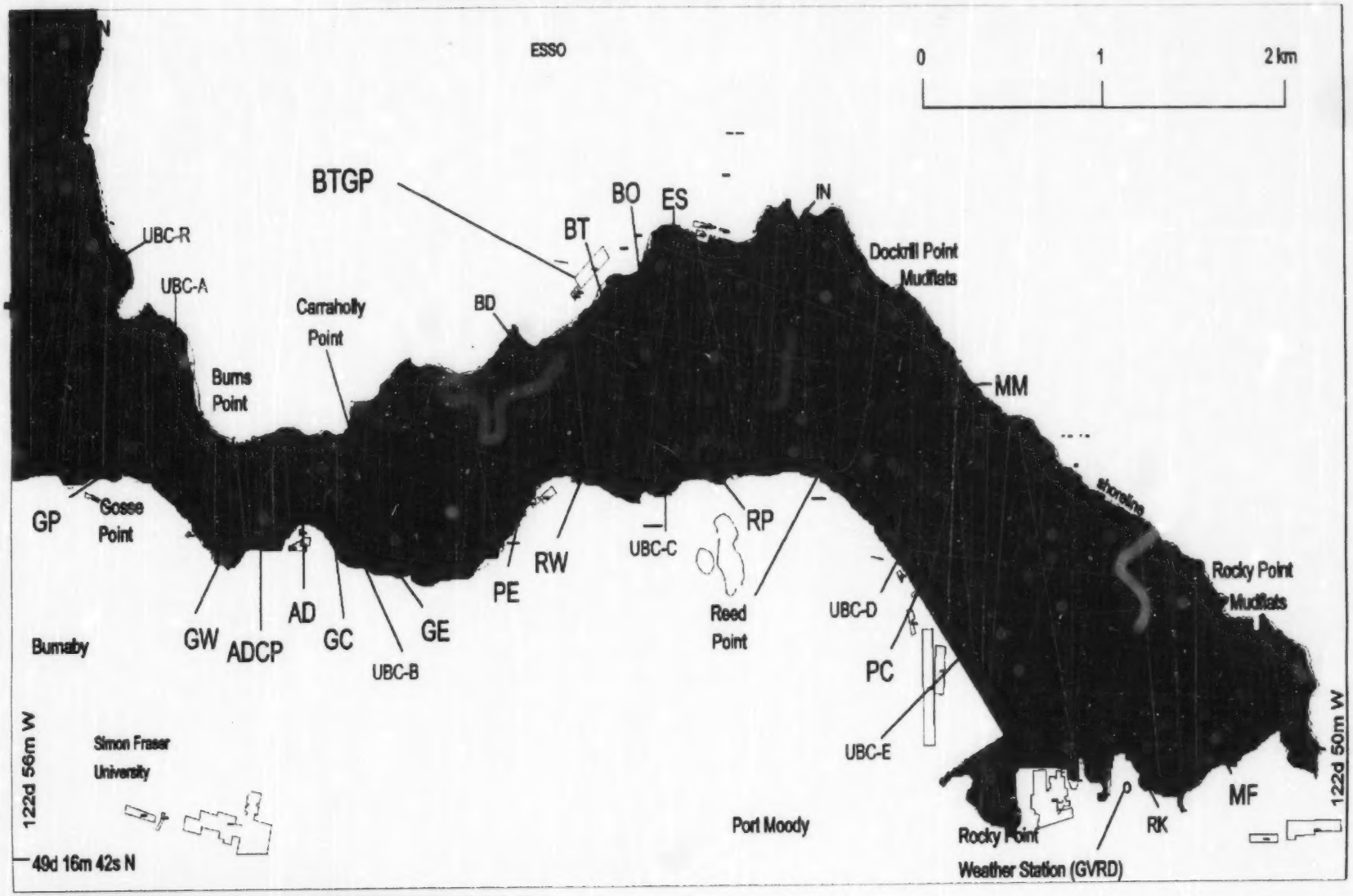
Port Moody Arm

0.5 m Water Temperatures, February 1998

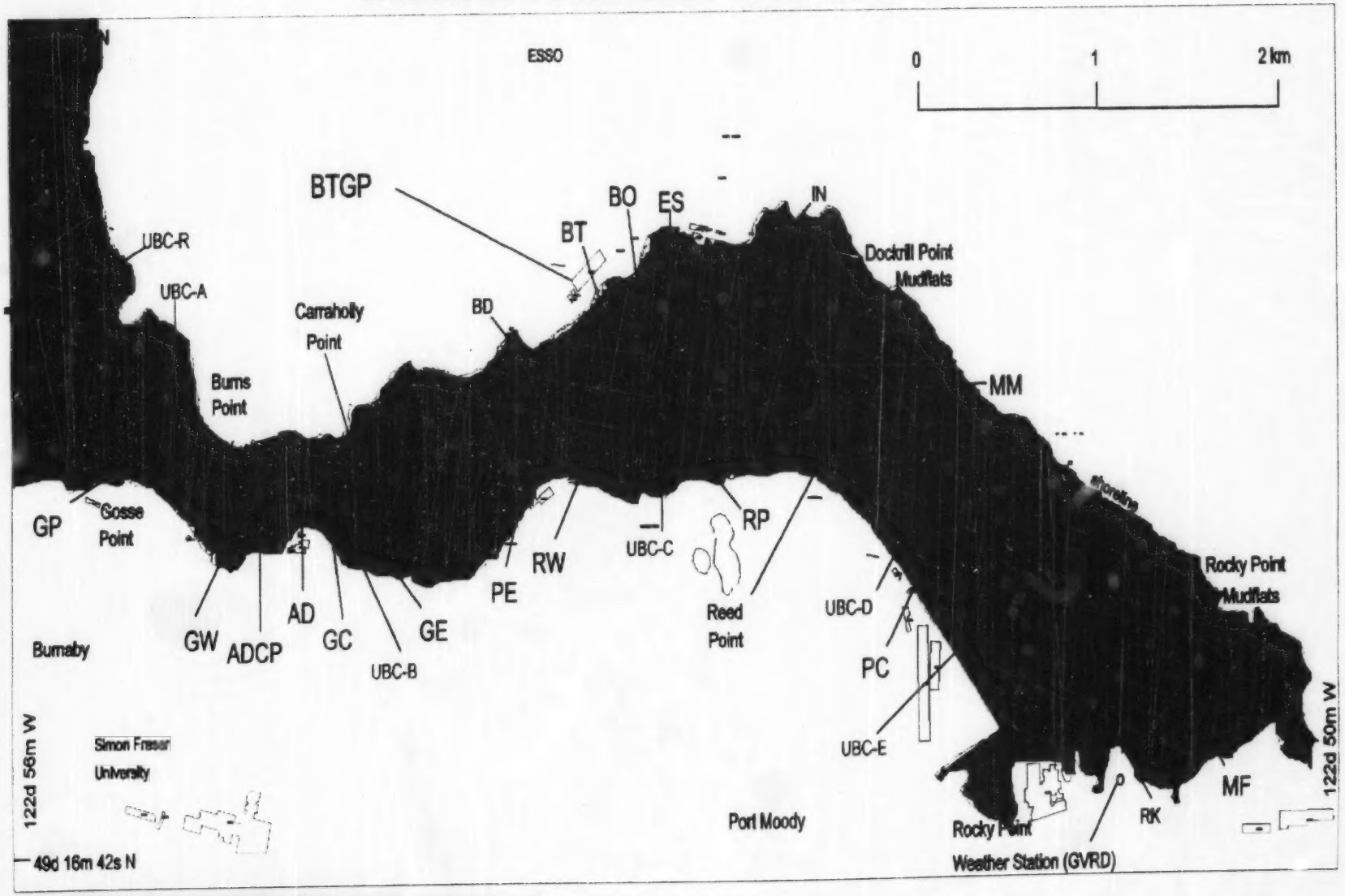


Contour Interval 0.05 degree Celsius

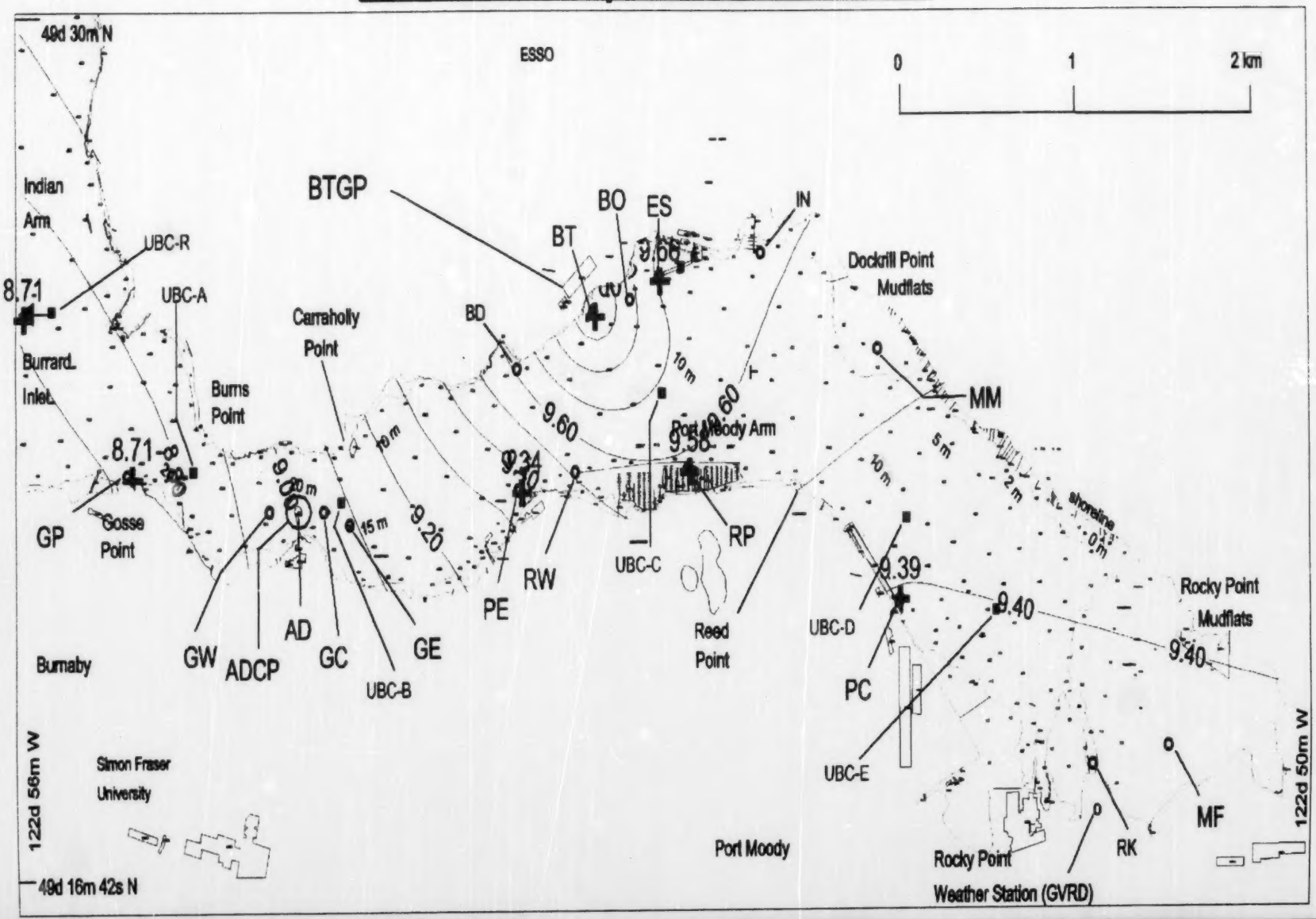
Port Moody Arm
2m Water Temperatures, February 1998



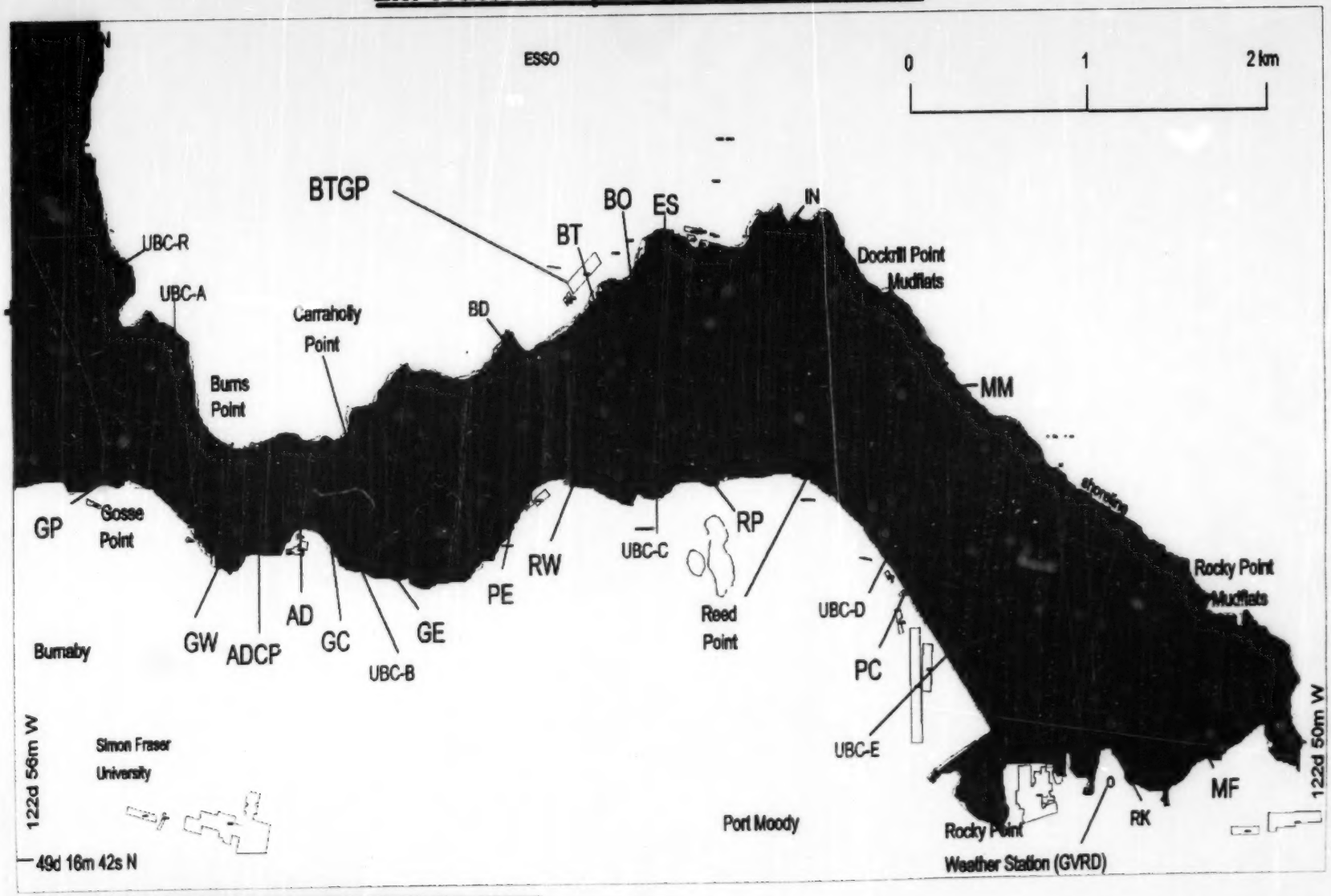
Port Moody Arm
5m Water Temperatures, February 1998



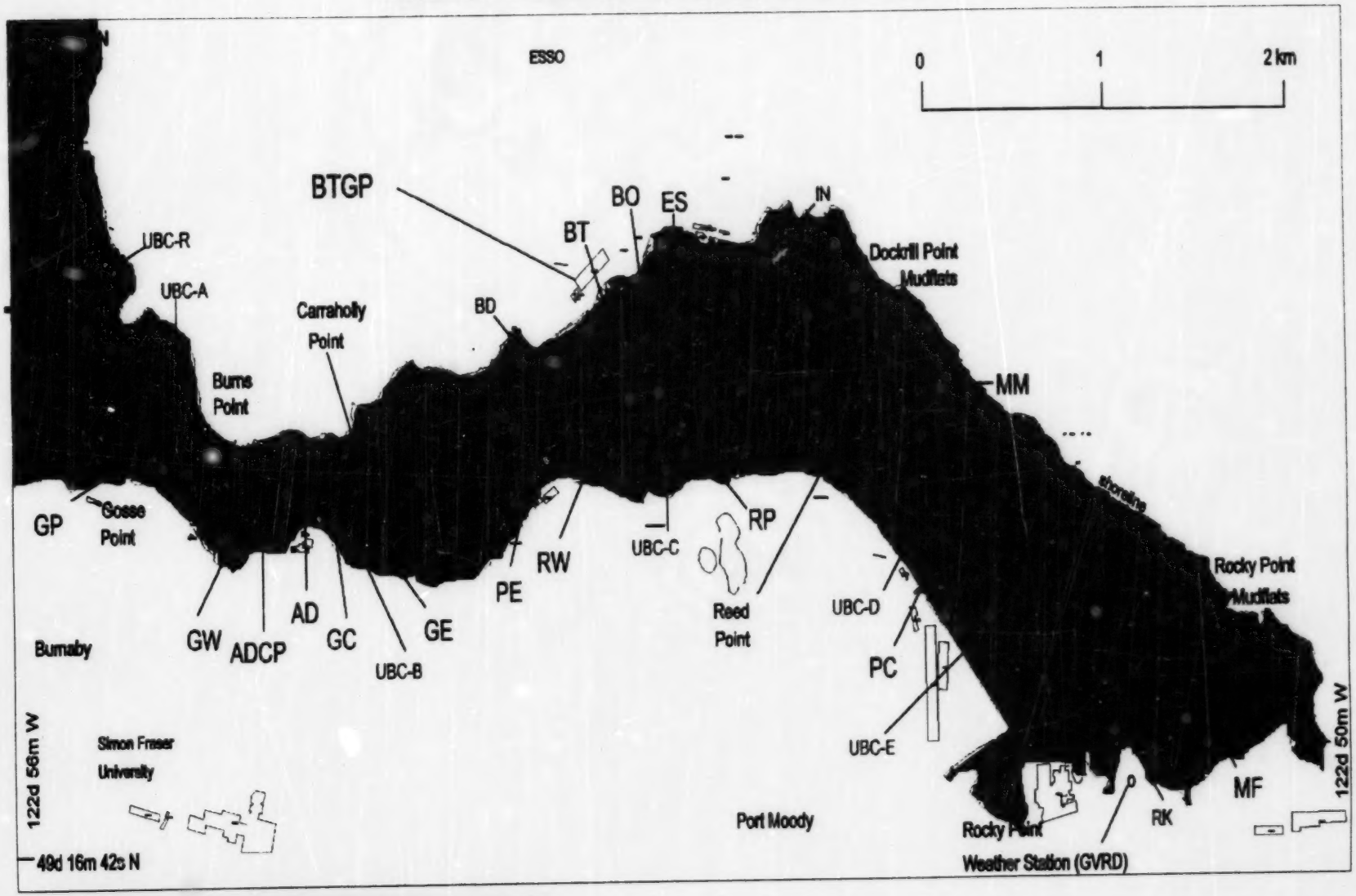
Port Moody Arm
0.5 m Water Temperatures, March 1998



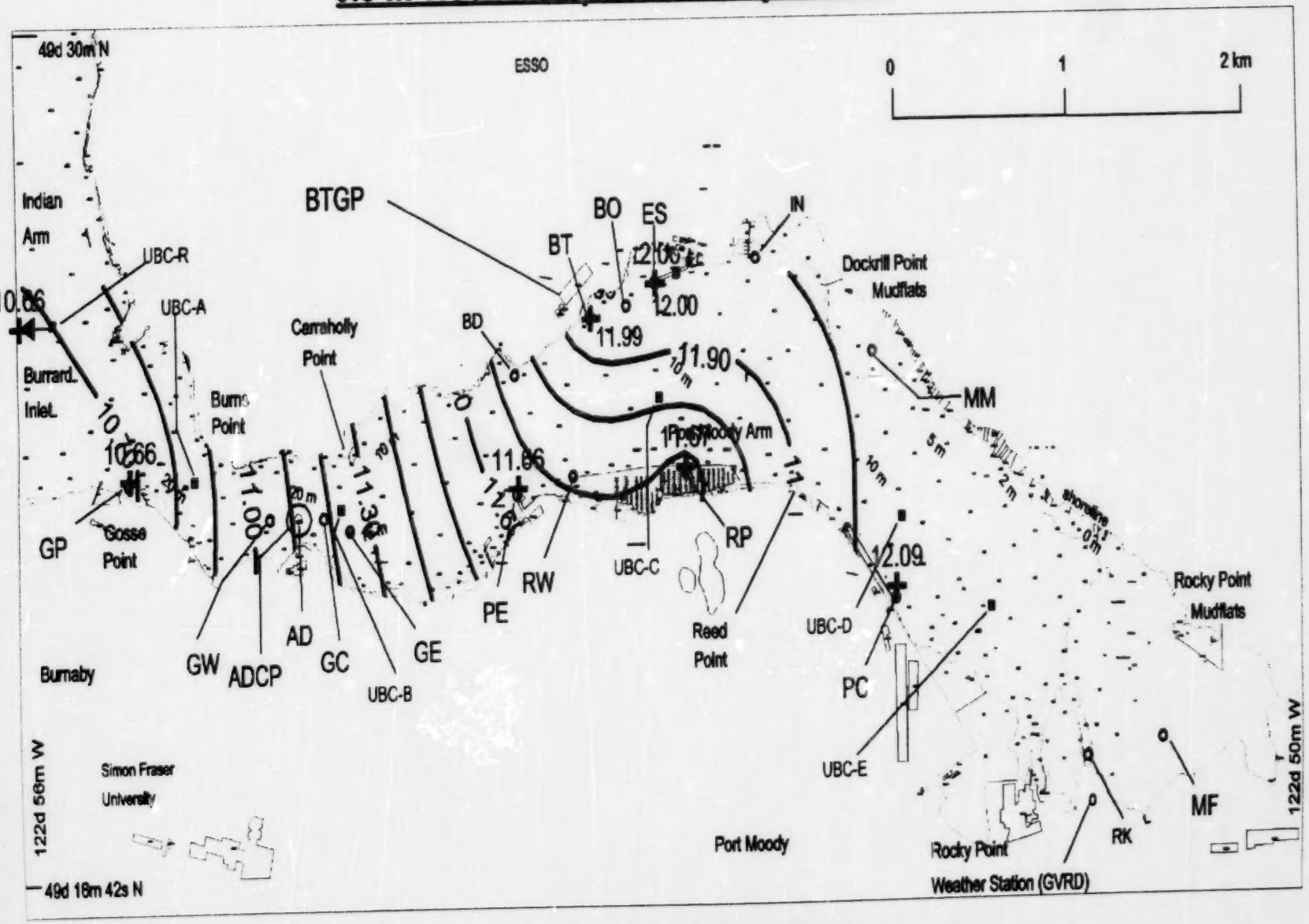
Port Moody Arm
2m Water Temperatures, March 1998



Port Moody Arm
5m Water Temperatures, March 1998

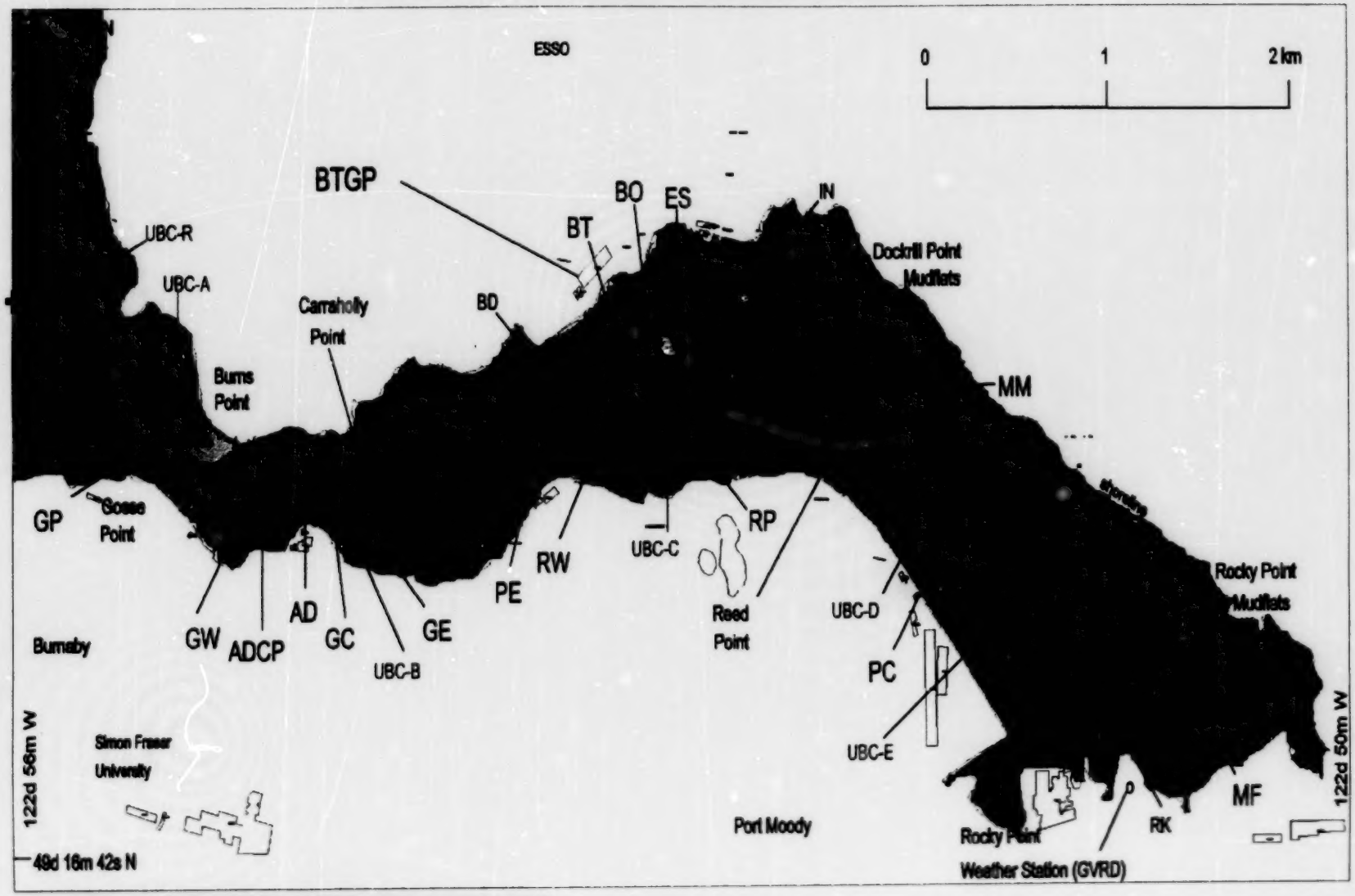


Port Moody Arm
0.5 m Water Temperatures, April 1998

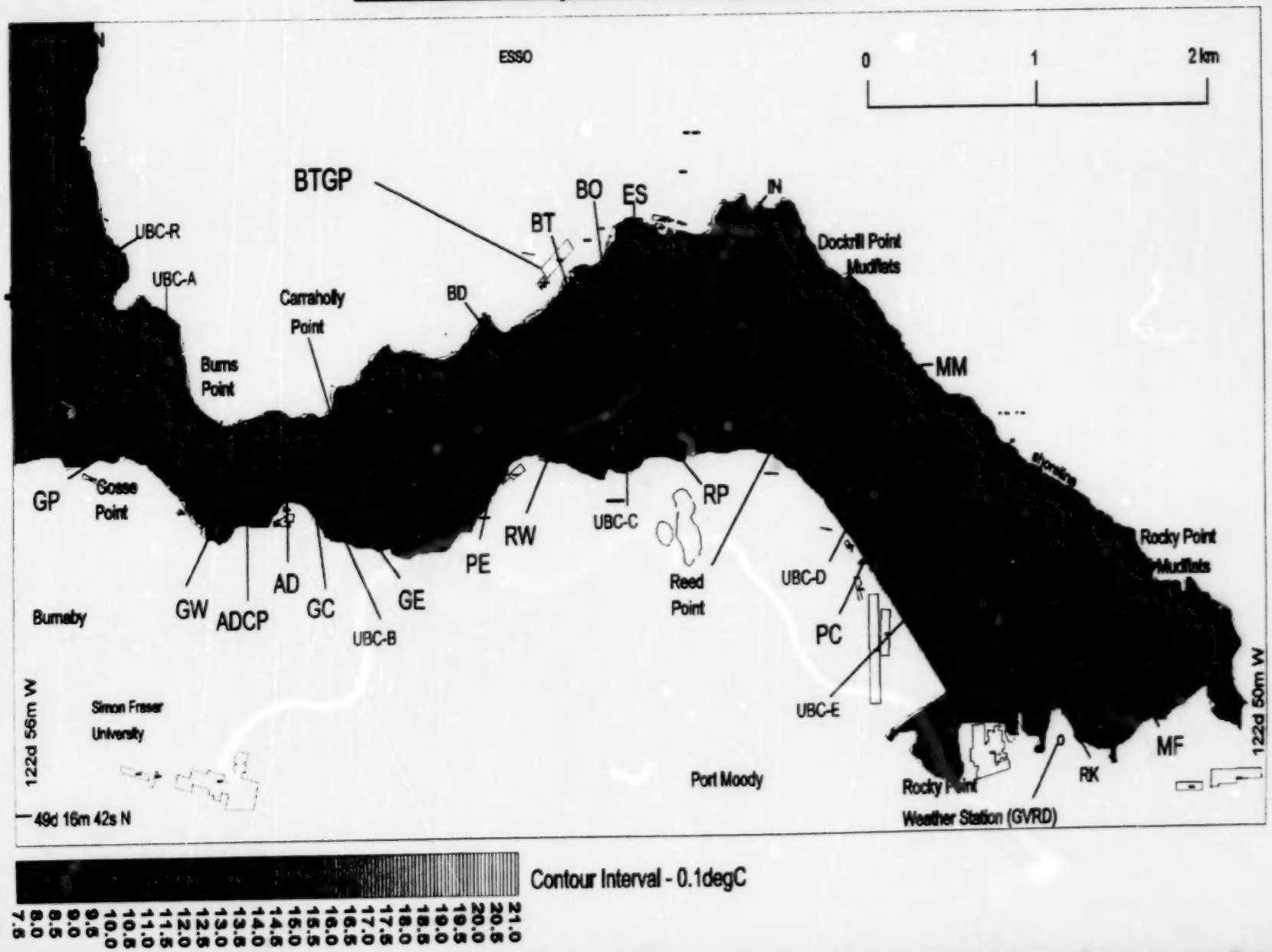


Contour Interval - 0.1degree Celsius

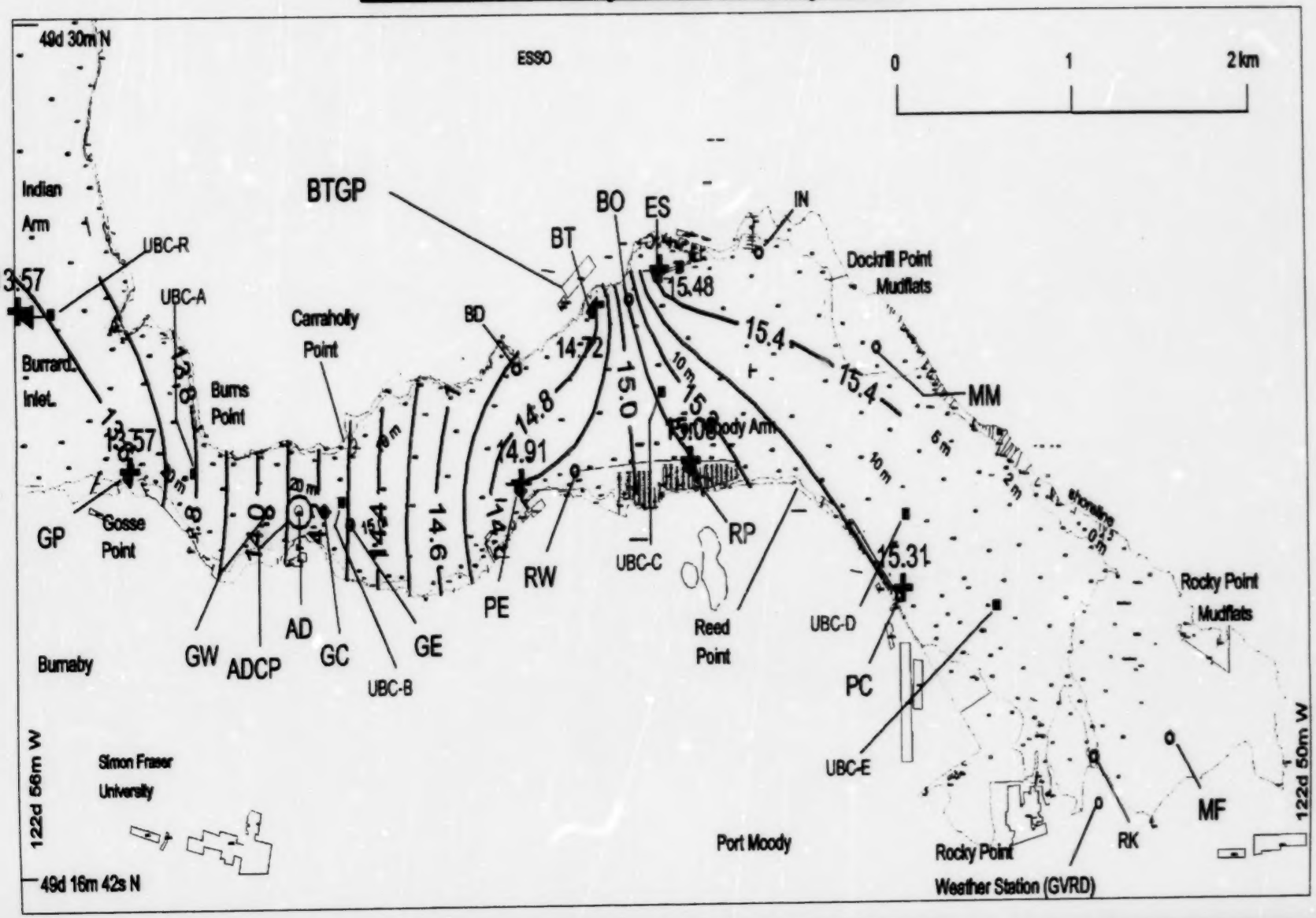
2m Water Temperatures, April 1998



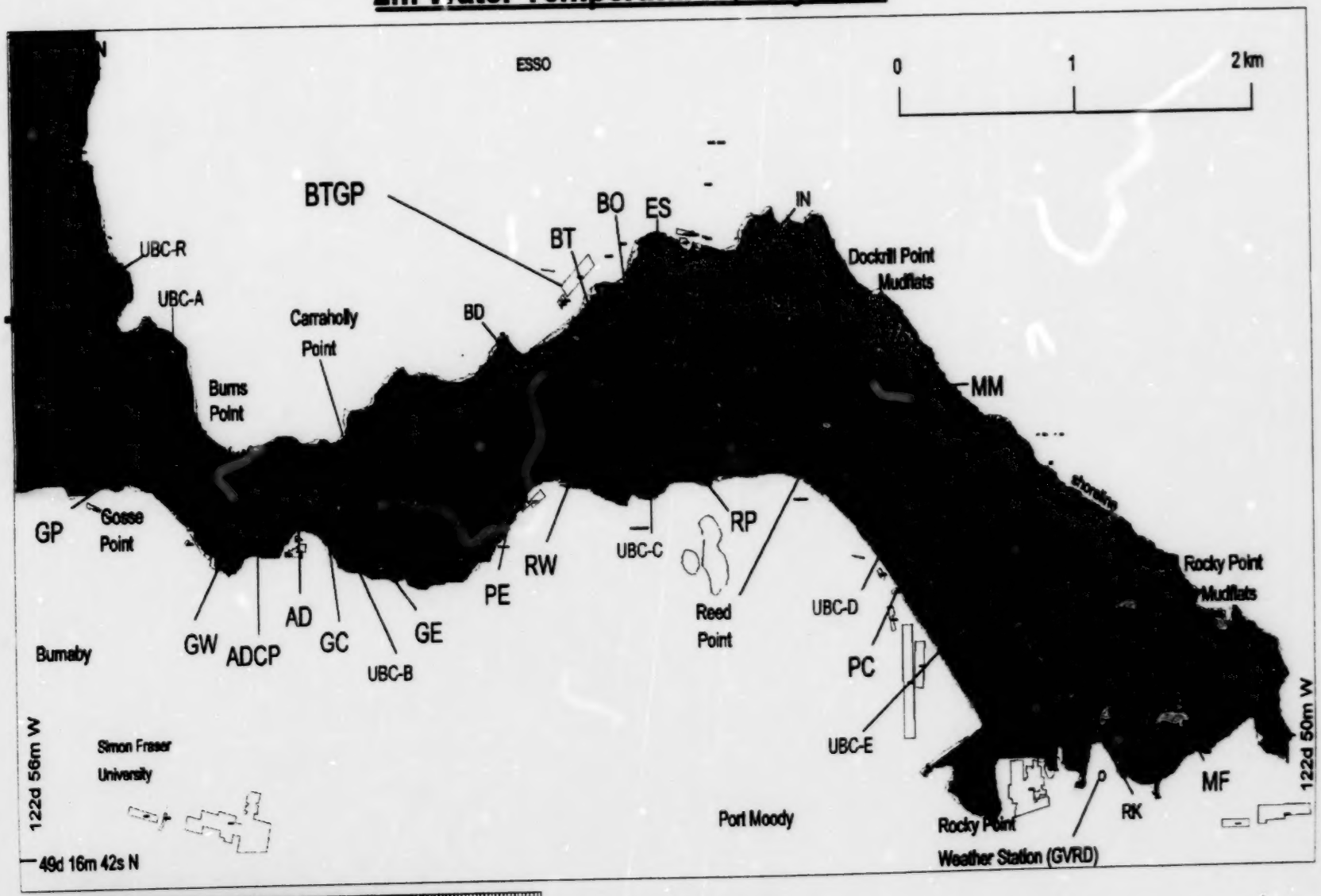
Port Moody Arm
5m Water Temperatures, April 1998



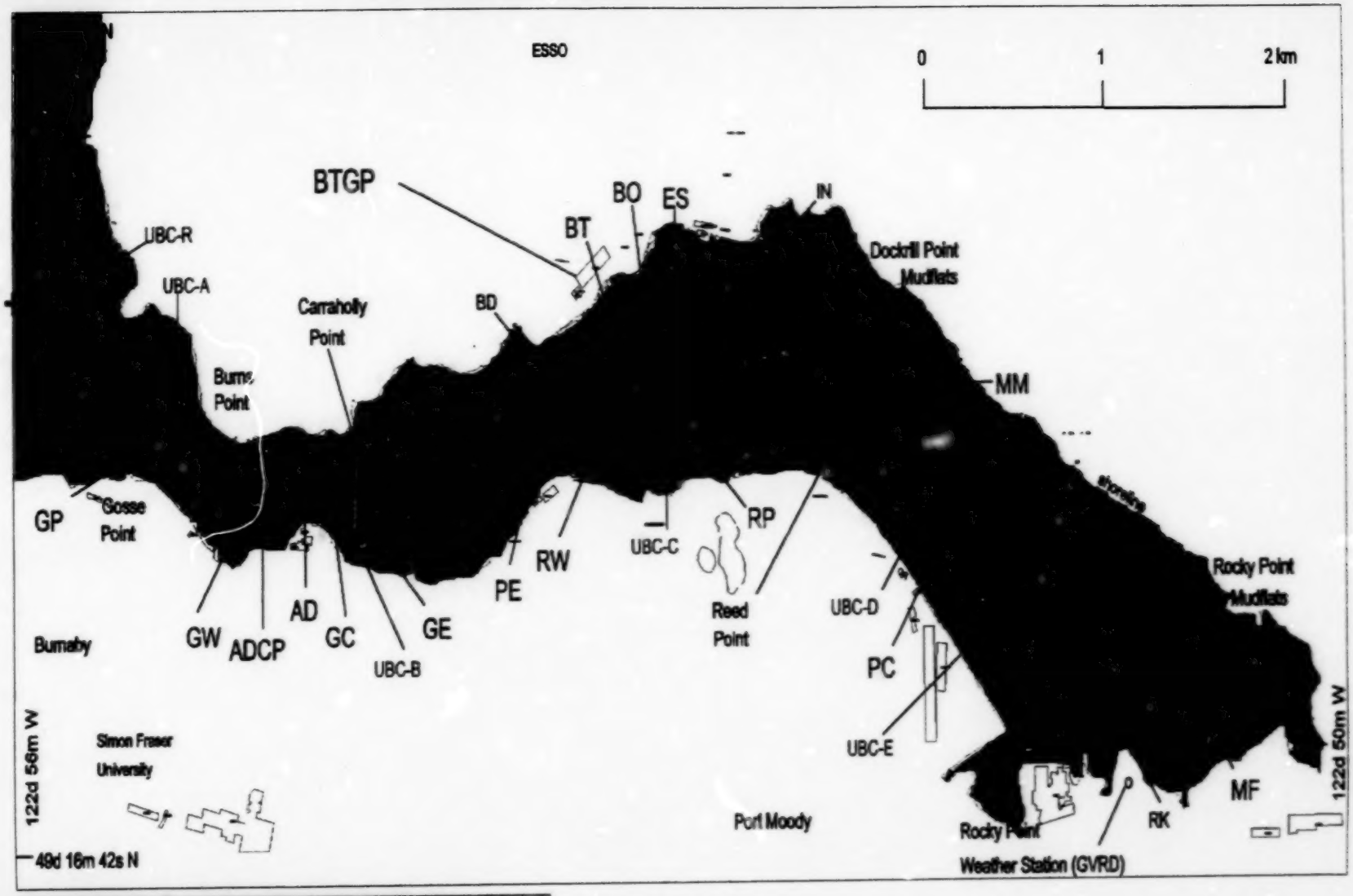
Port Moody Arm
0.5 m Water Temperatures, May 1998



Port Moody Arm
2m Water Temperatures, May 1998

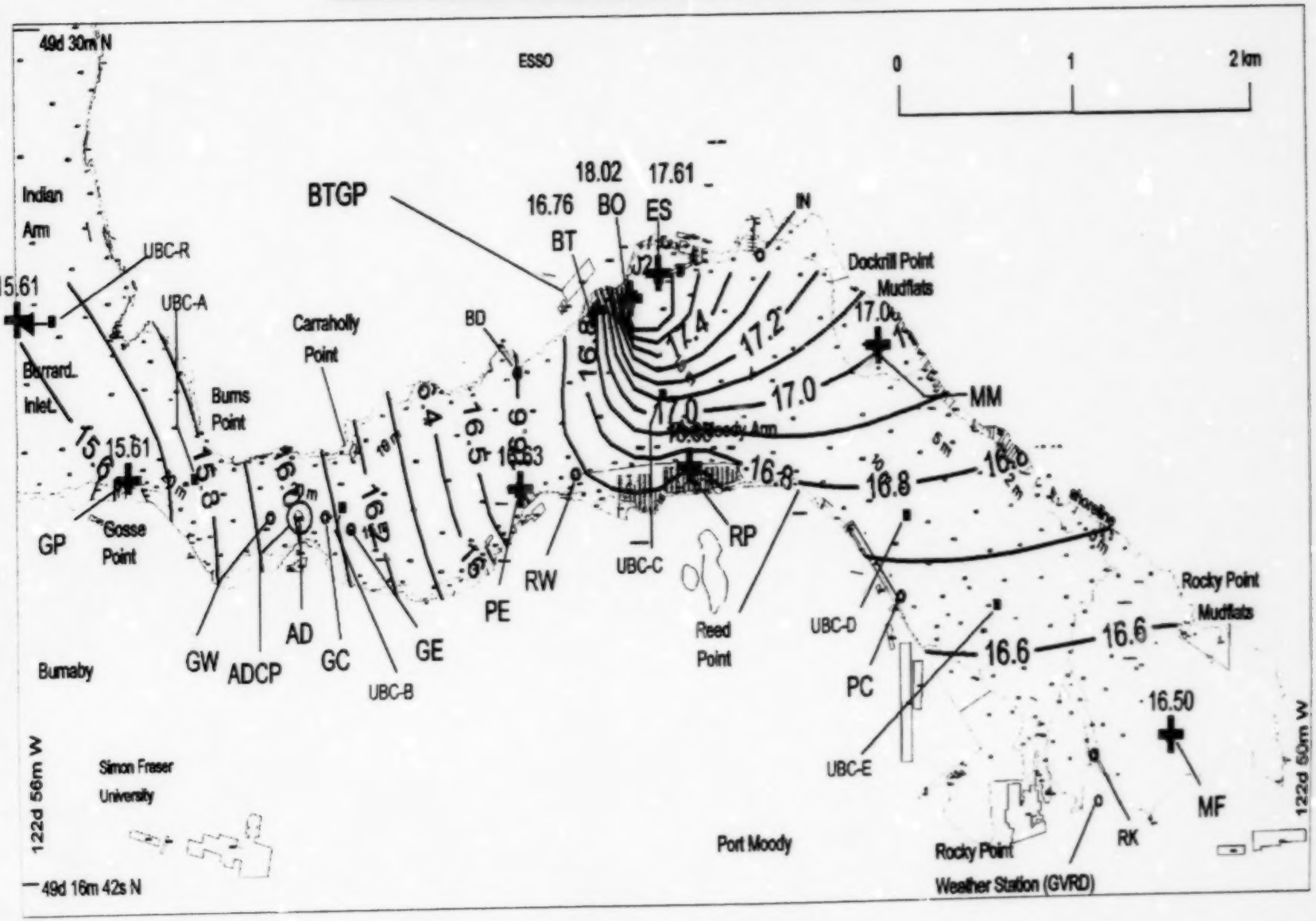


Port Moody Arm
5m Water Temperatures, May 1998



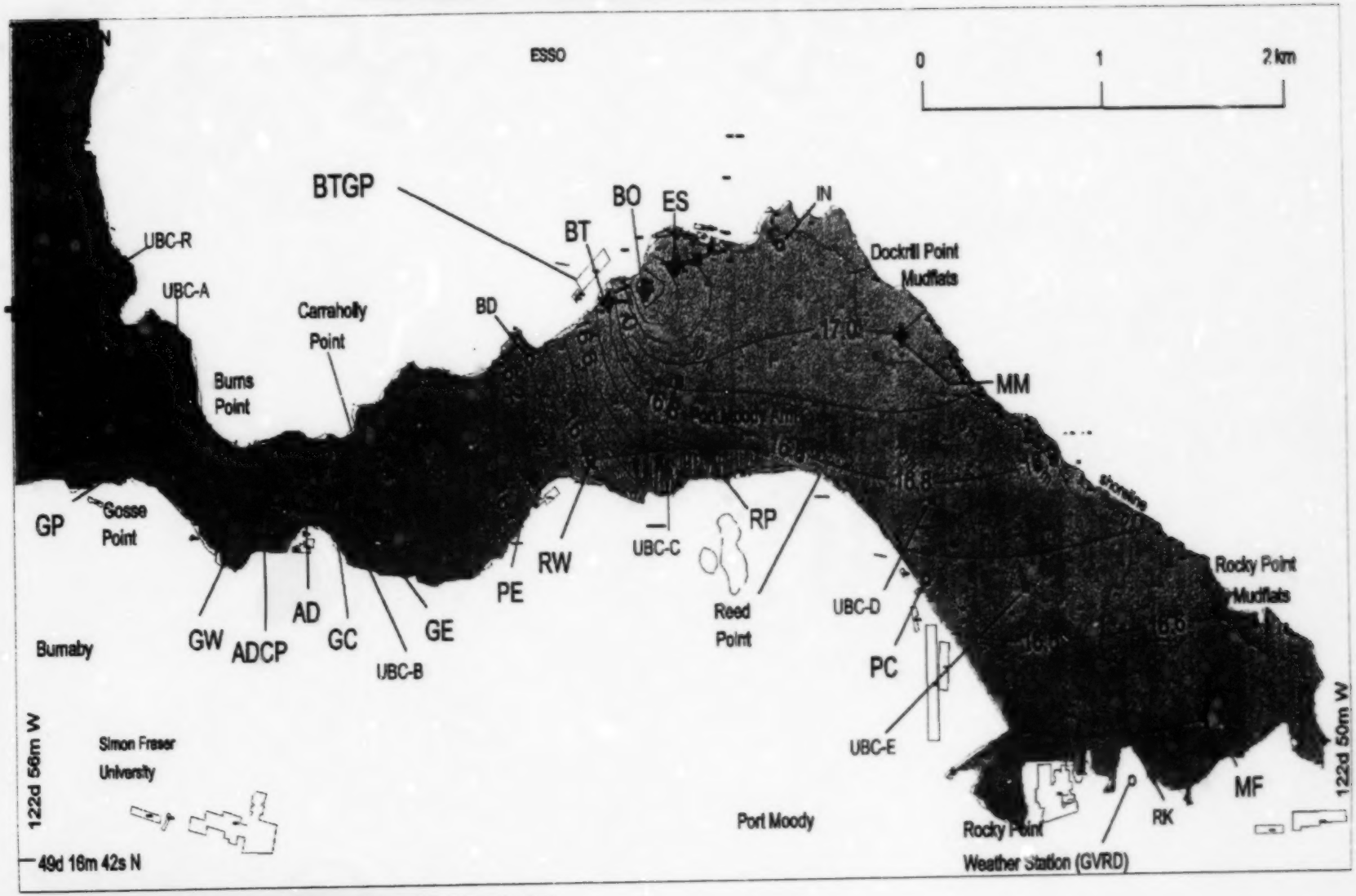
Port Moody Arm

0.5 m Water Temperatures, June 1998



Contour Interval - 0.1 degree Celsius

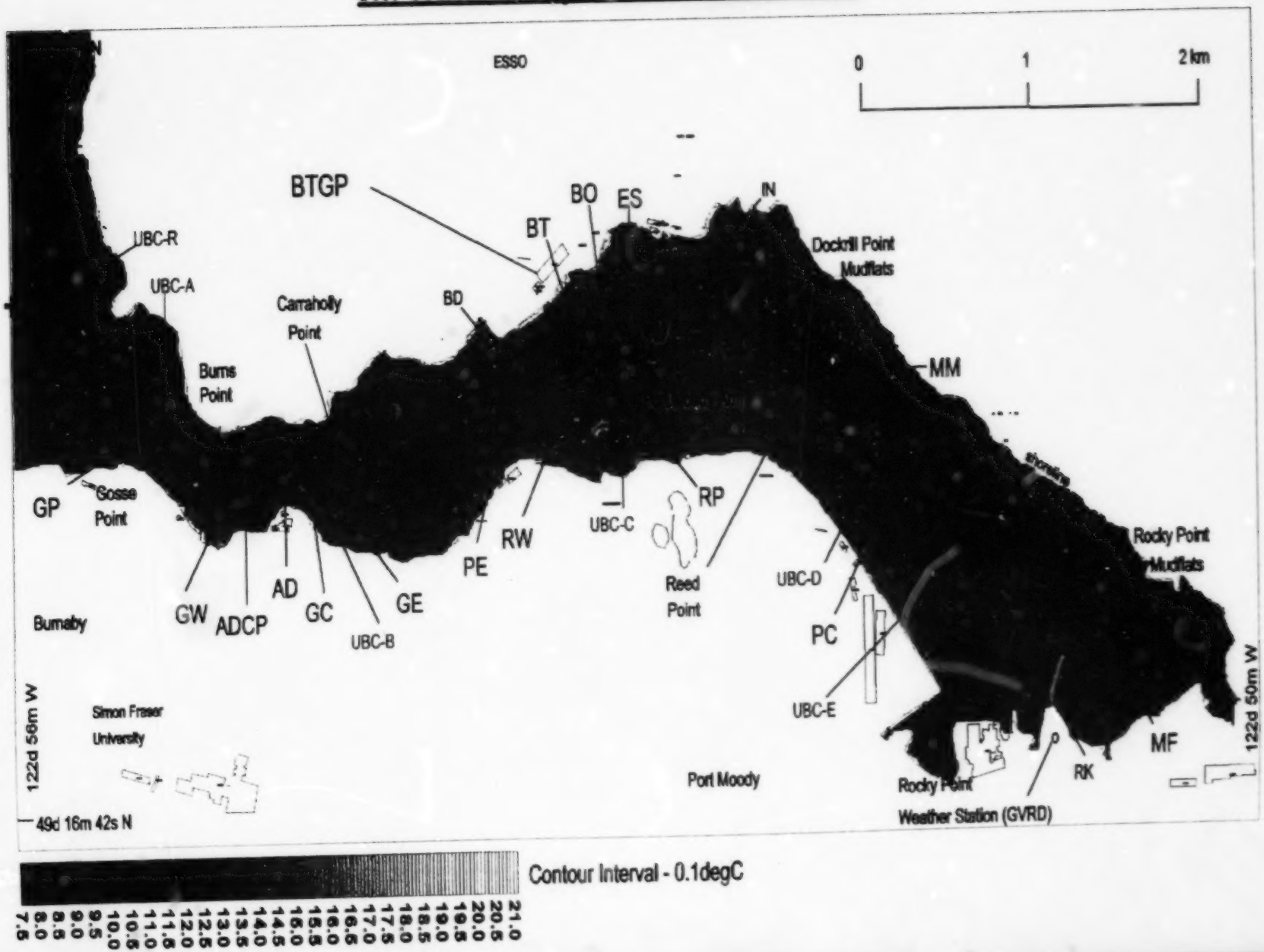
Port Moody Arm
2m Water Temperatures, June 1998



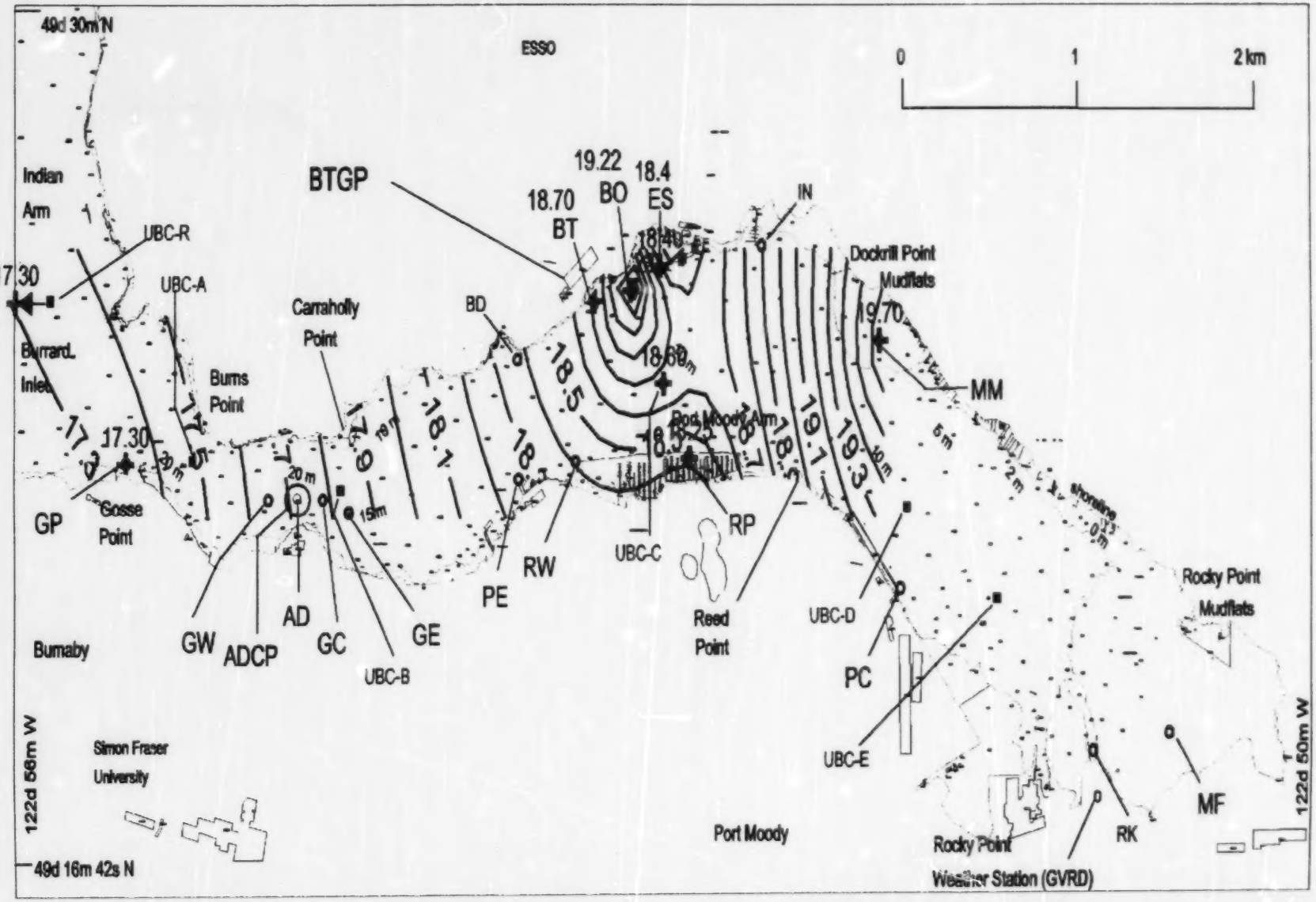
Contour Interval - 0.1degC

Port Moody Arm

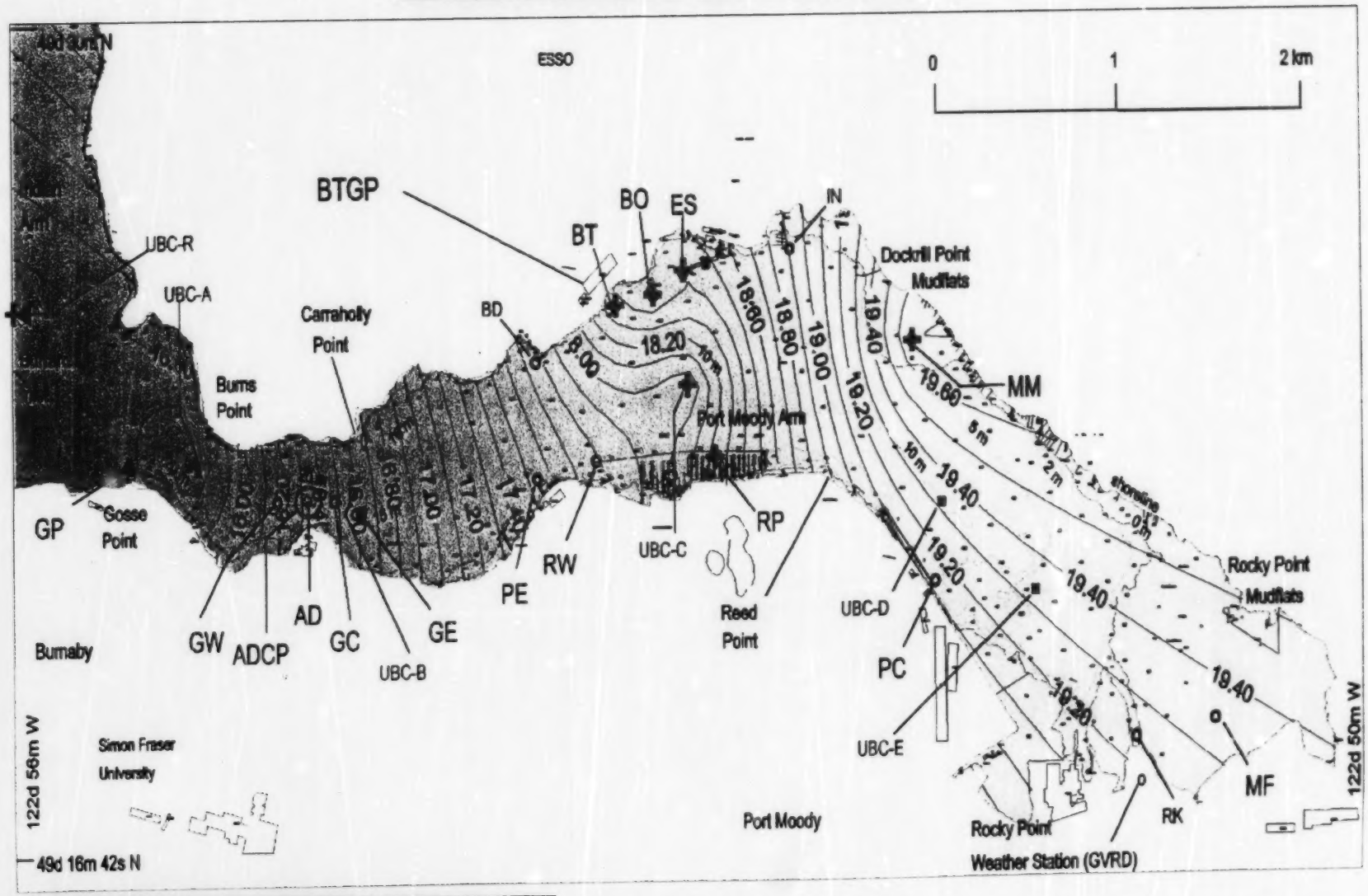
5m Water Temperatures, June 1998



Port Moody Arm
0.5 m Water Temperatures, July 1998



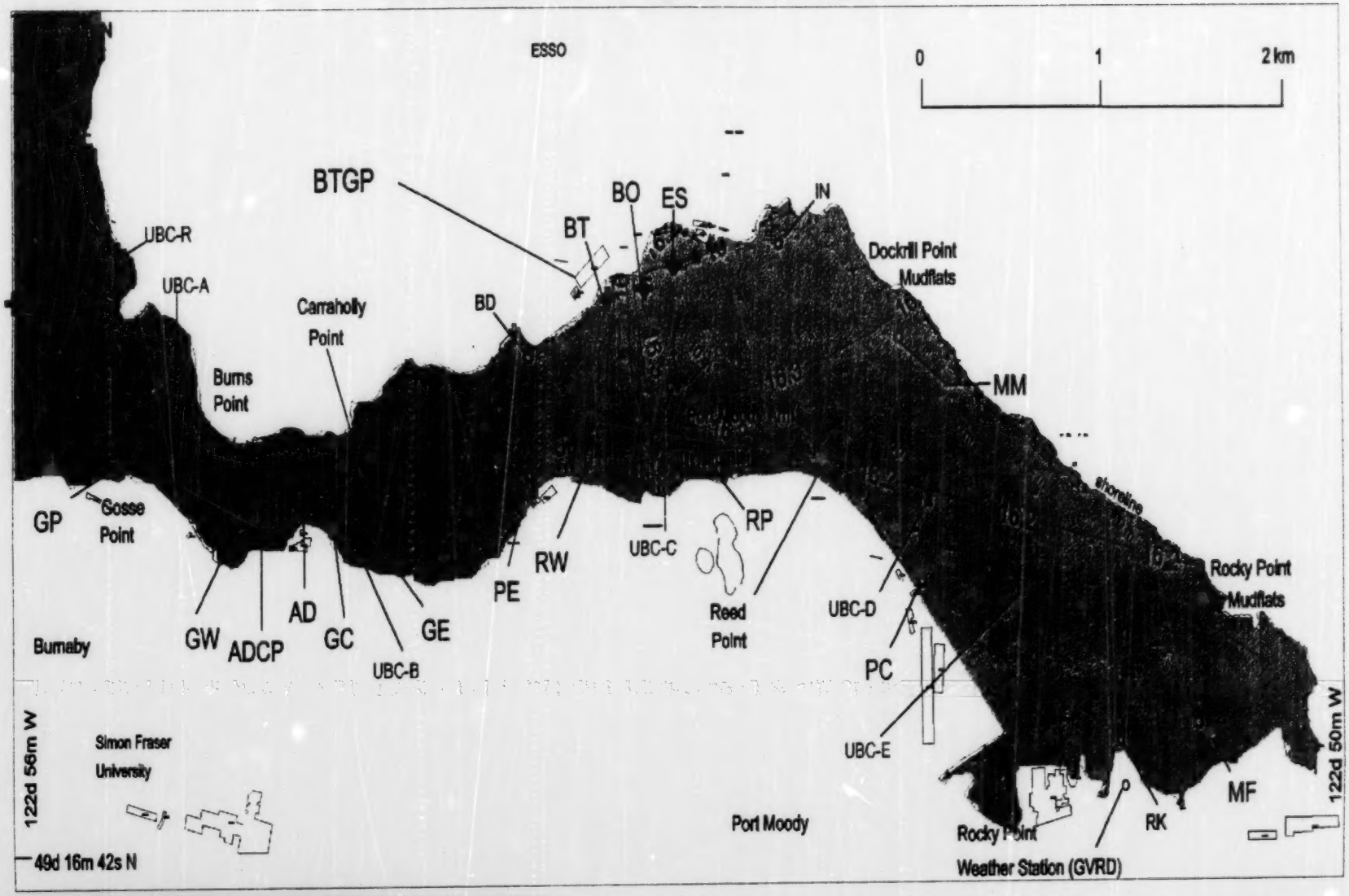
Port Moody Arm
2m Water Temperatures, July 1998



Contour Interval - 0.1degC

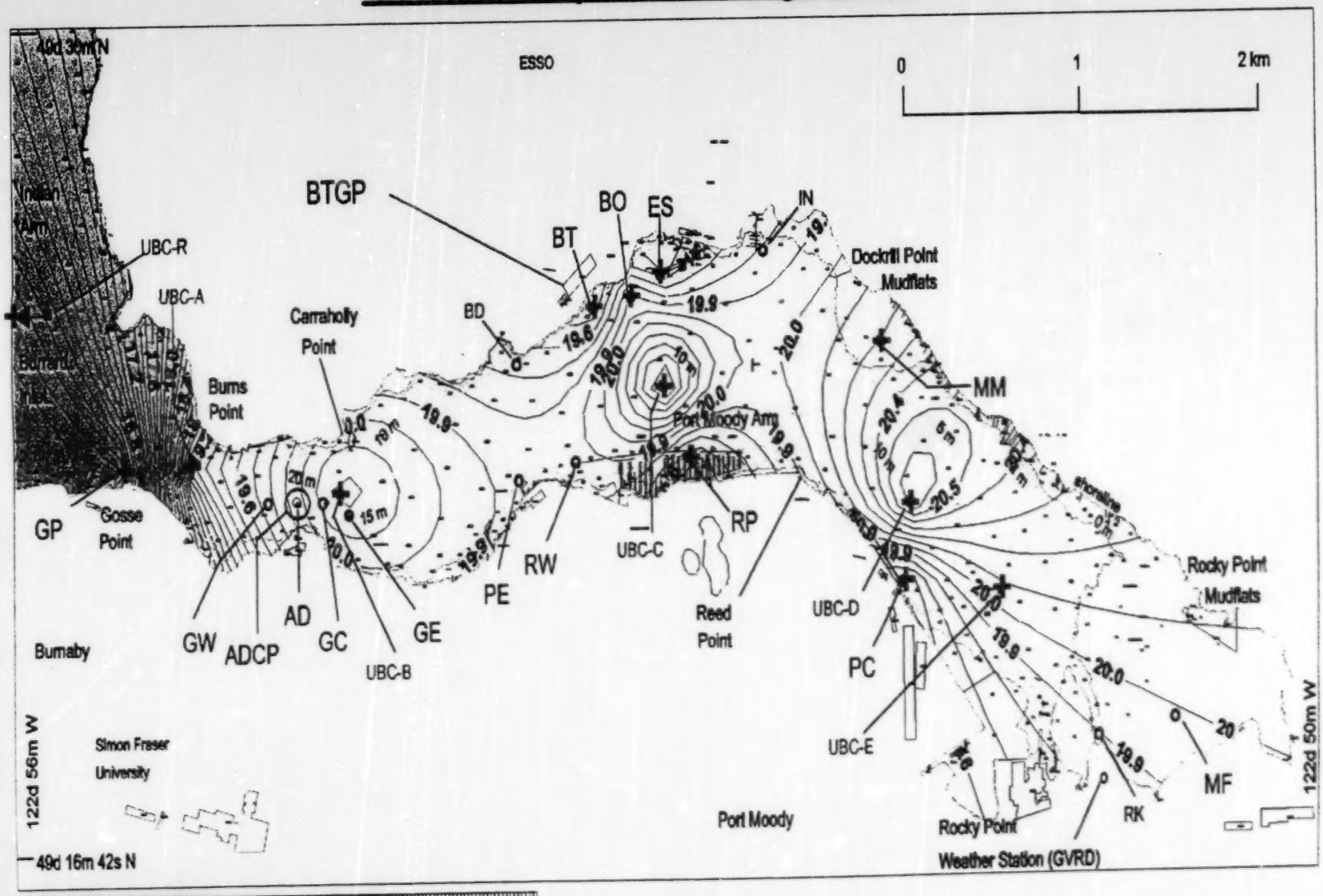
20.70 20.10 19.50 18.90 18.30 17.70 17.10 16.50 15.90 15.30 13.50 14.10 14.70 13.50 12.90 12.30 11.70 11.10 10.50 9.90 9.30 8.70 8.10 7.50

Port Moody Arm
5m Water Temperatures, July 1998

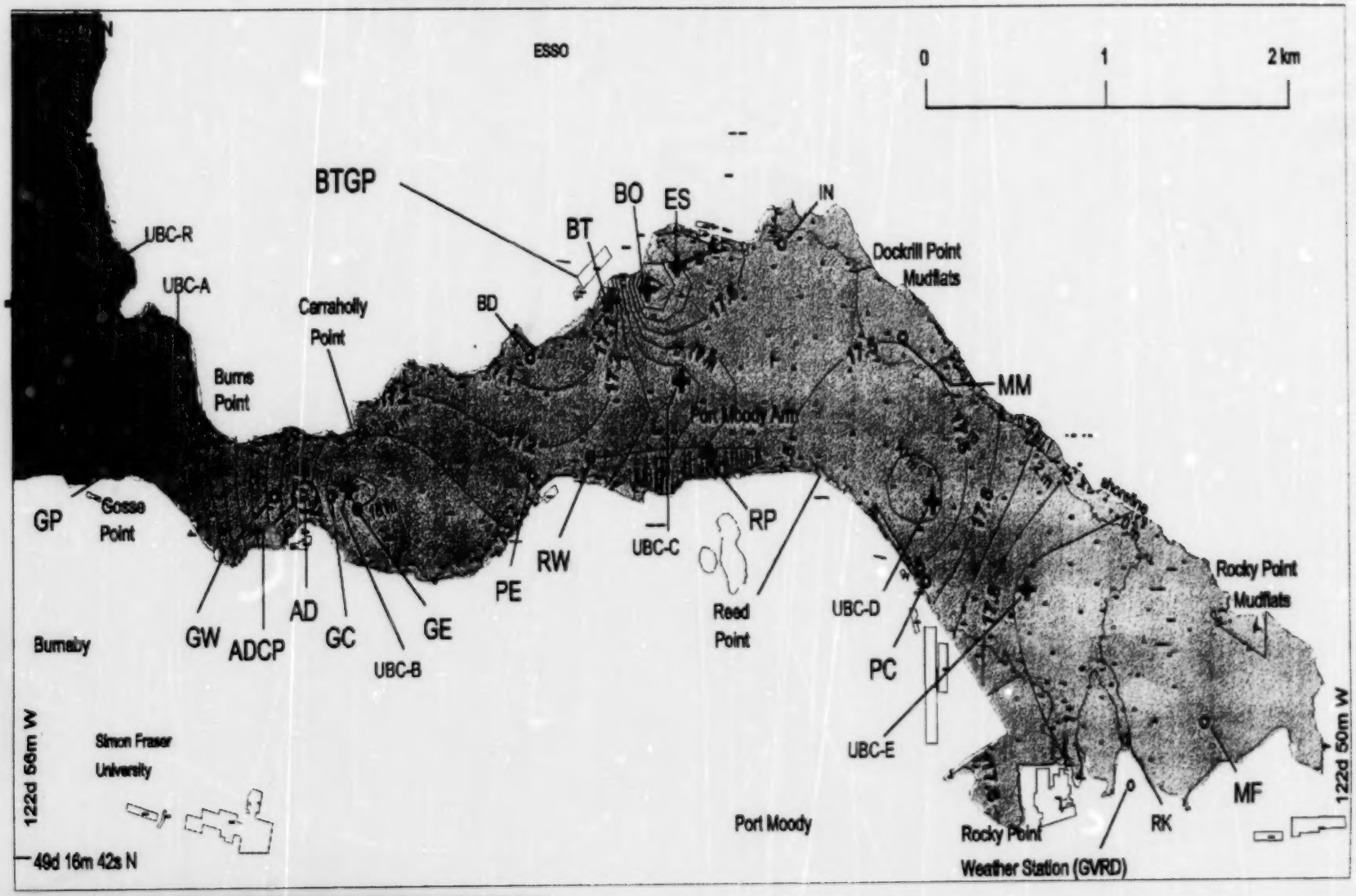


Contour Interval - 0.1degC

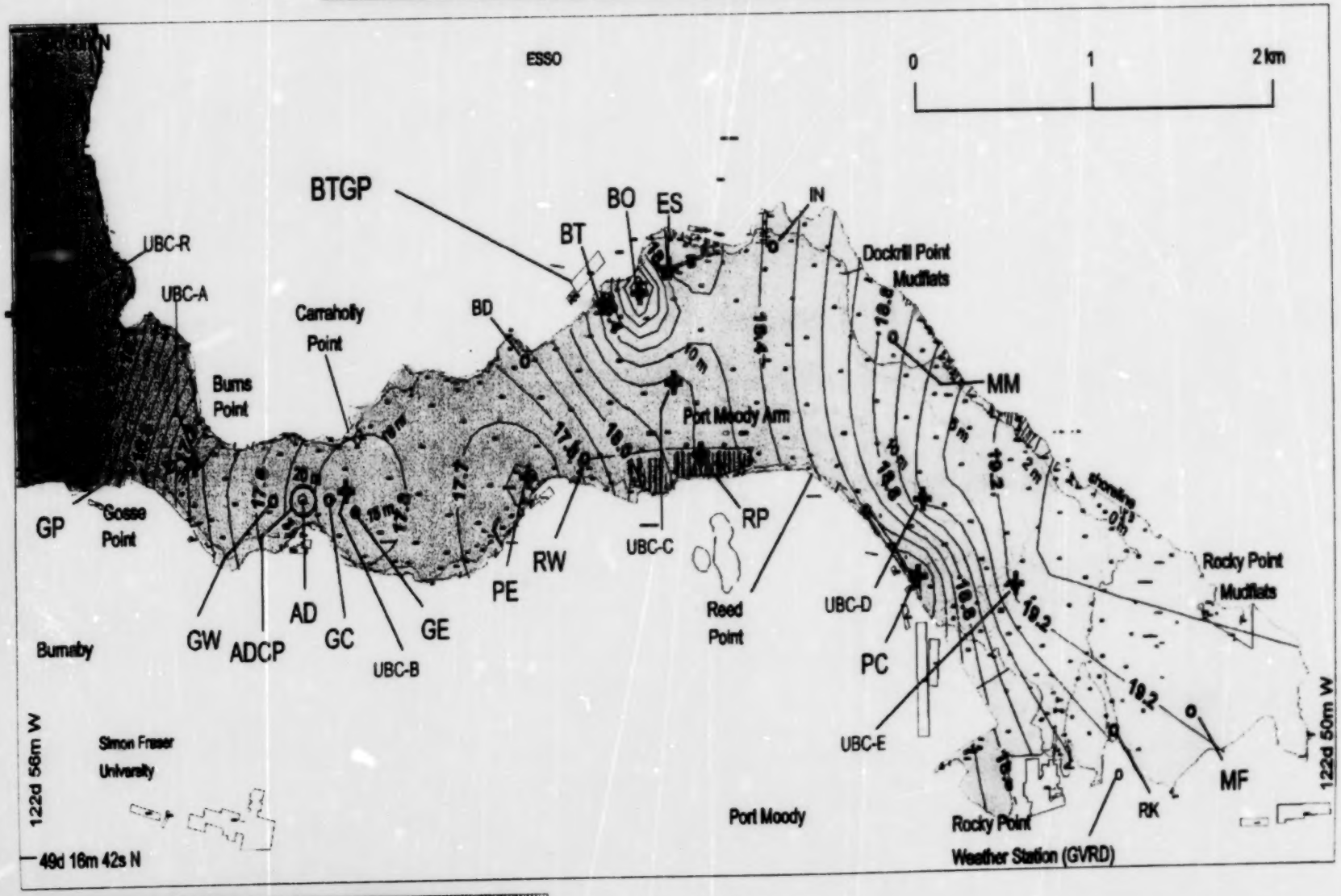
Port Moody Arm
2m Water Temperatures, August 1998



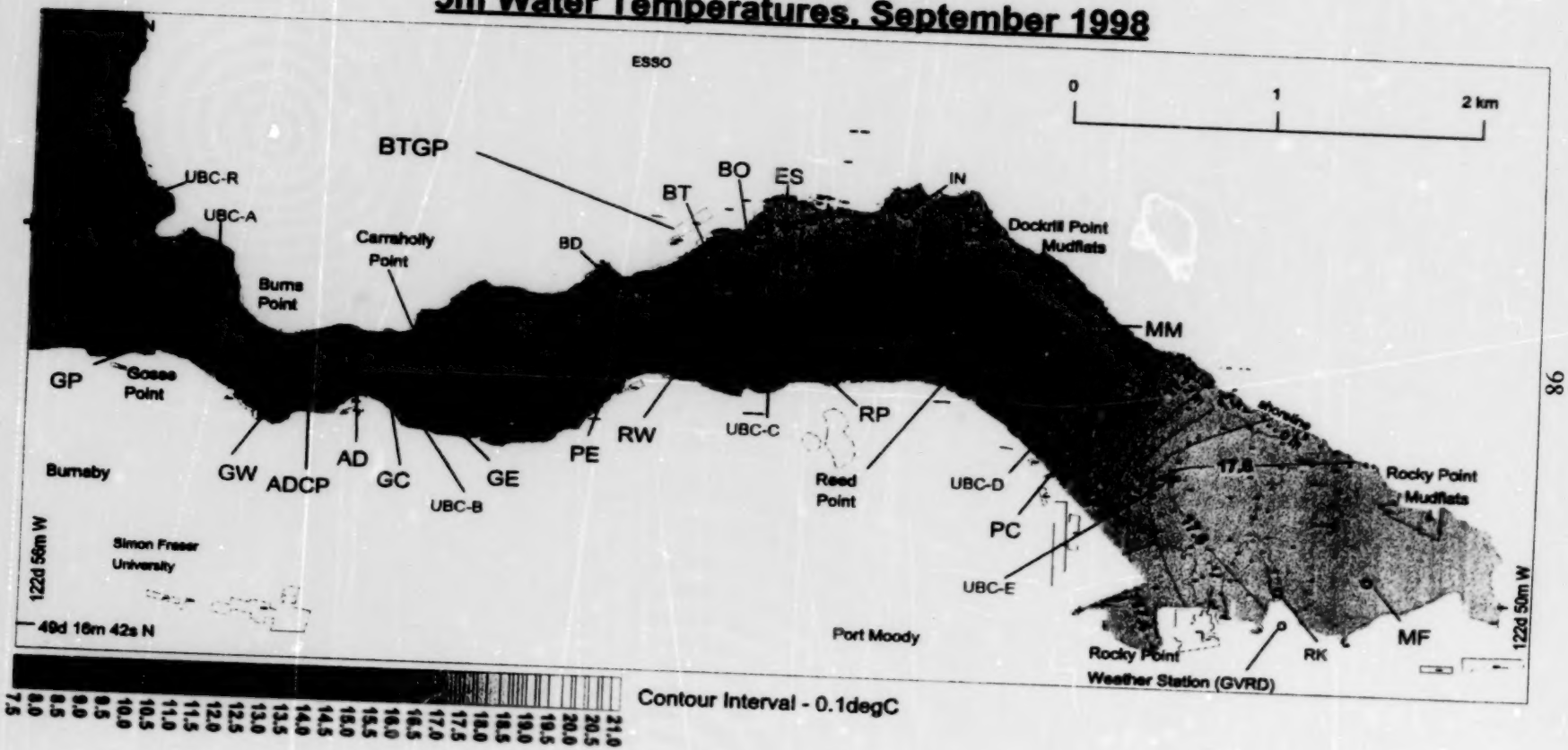
Port Moody Arm
5m Water Temperatures, August 1998



Port Moody Arm
2m Water Temperatures, September 1998

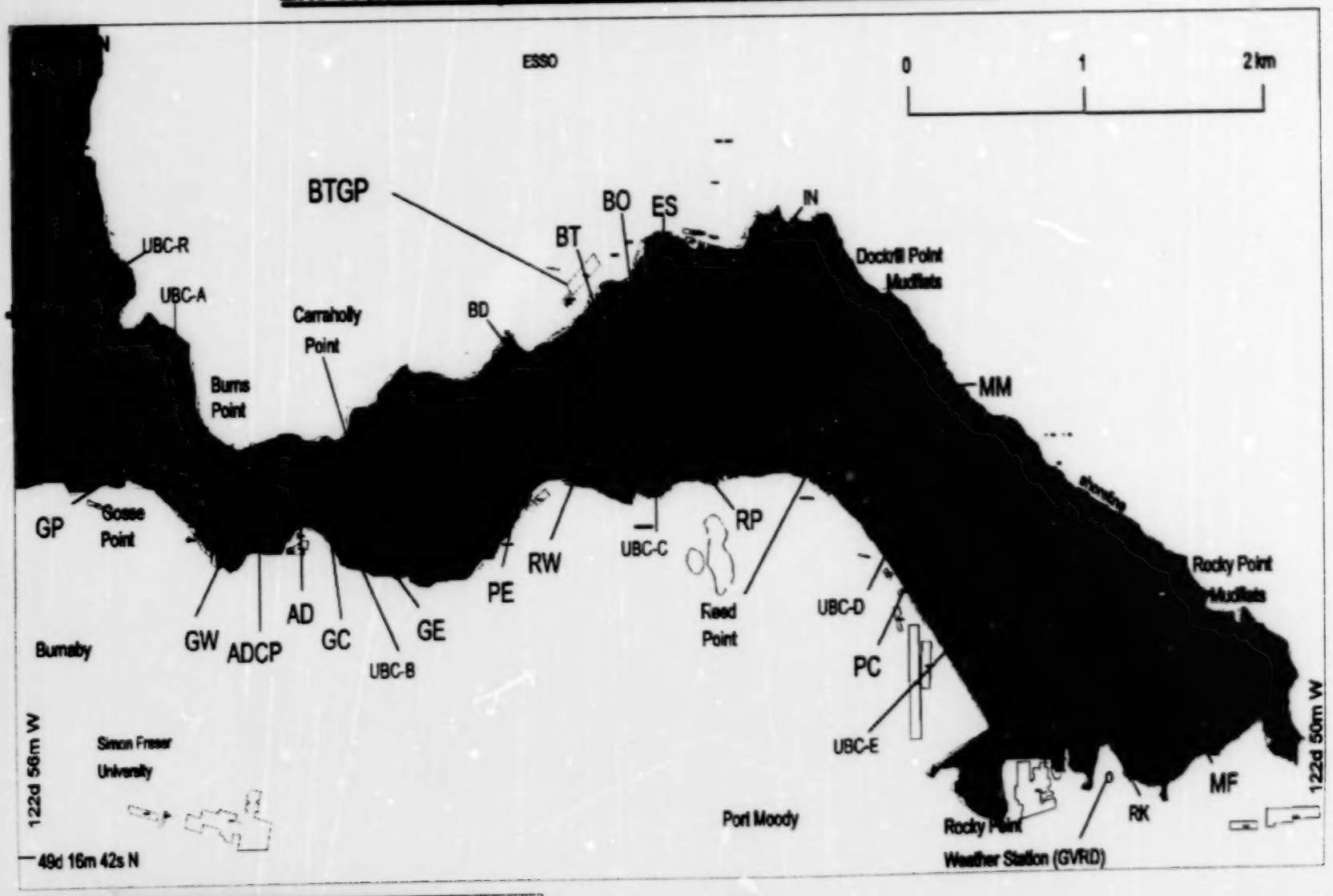


Port Moody Arm
5m Water Temperatures, September 1998

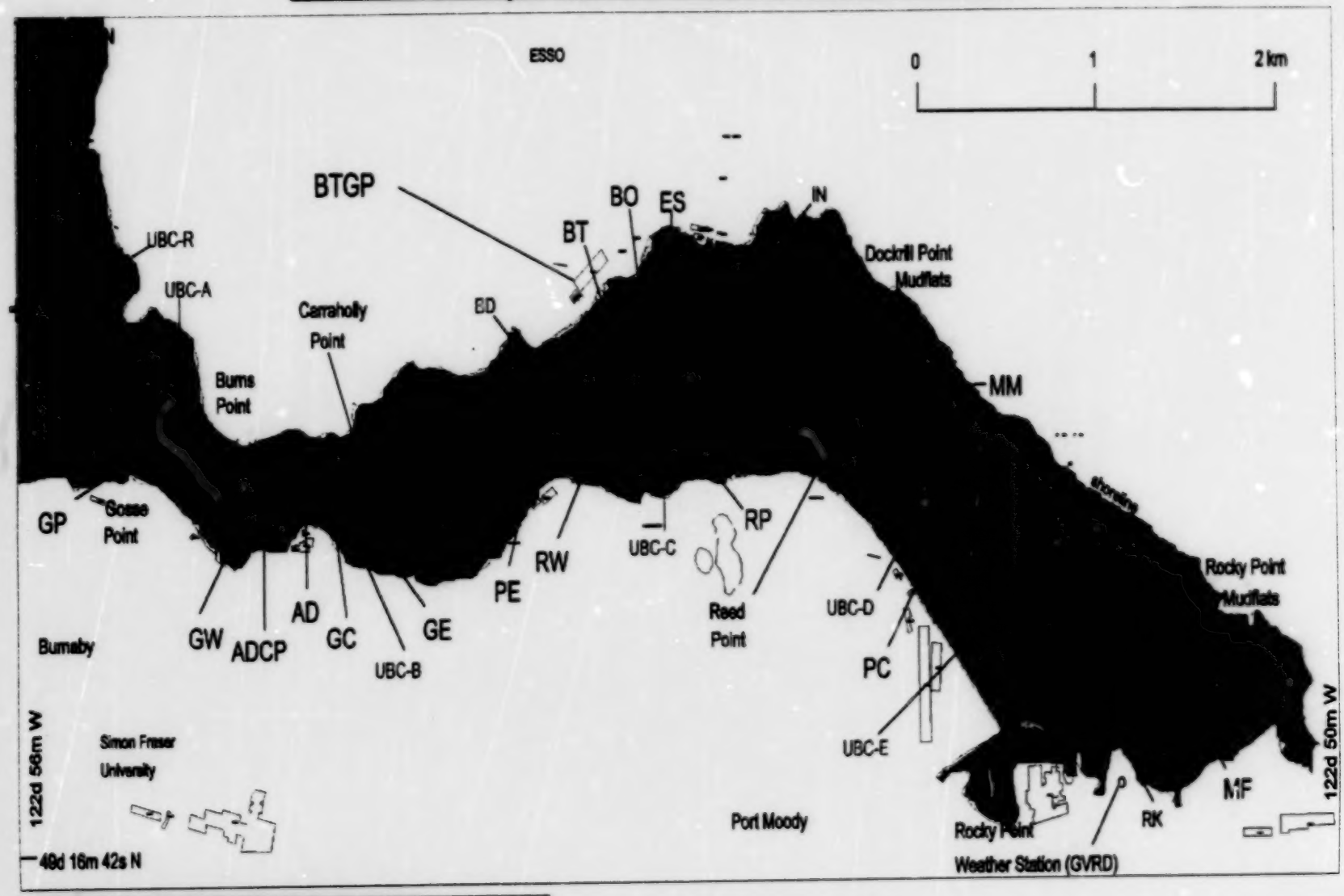


Port Moody Arm

2m Water Temperatures, Noon, October 29 1998



Port Moody Arm
5m Water Temperatures, Noon, October 29 1998

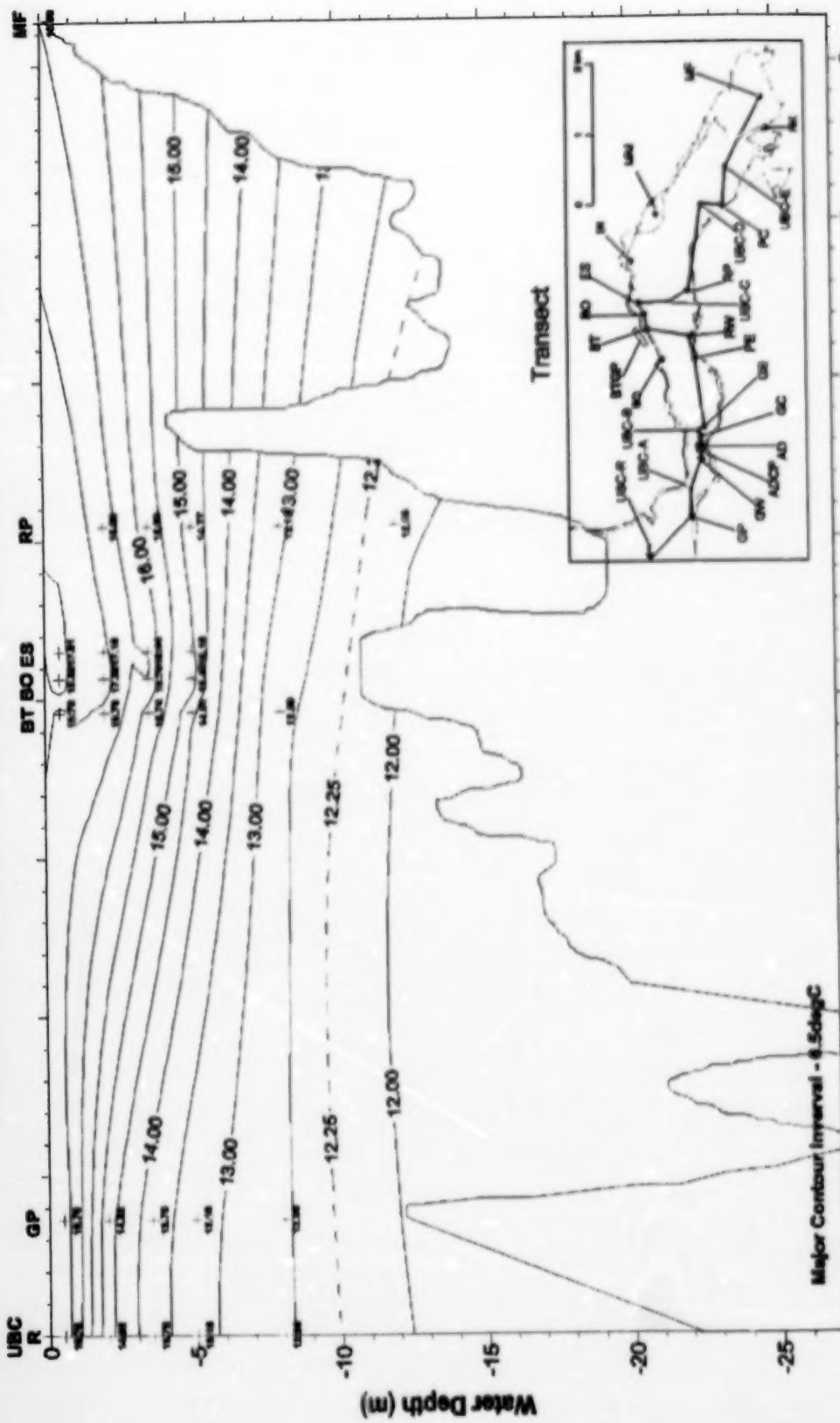


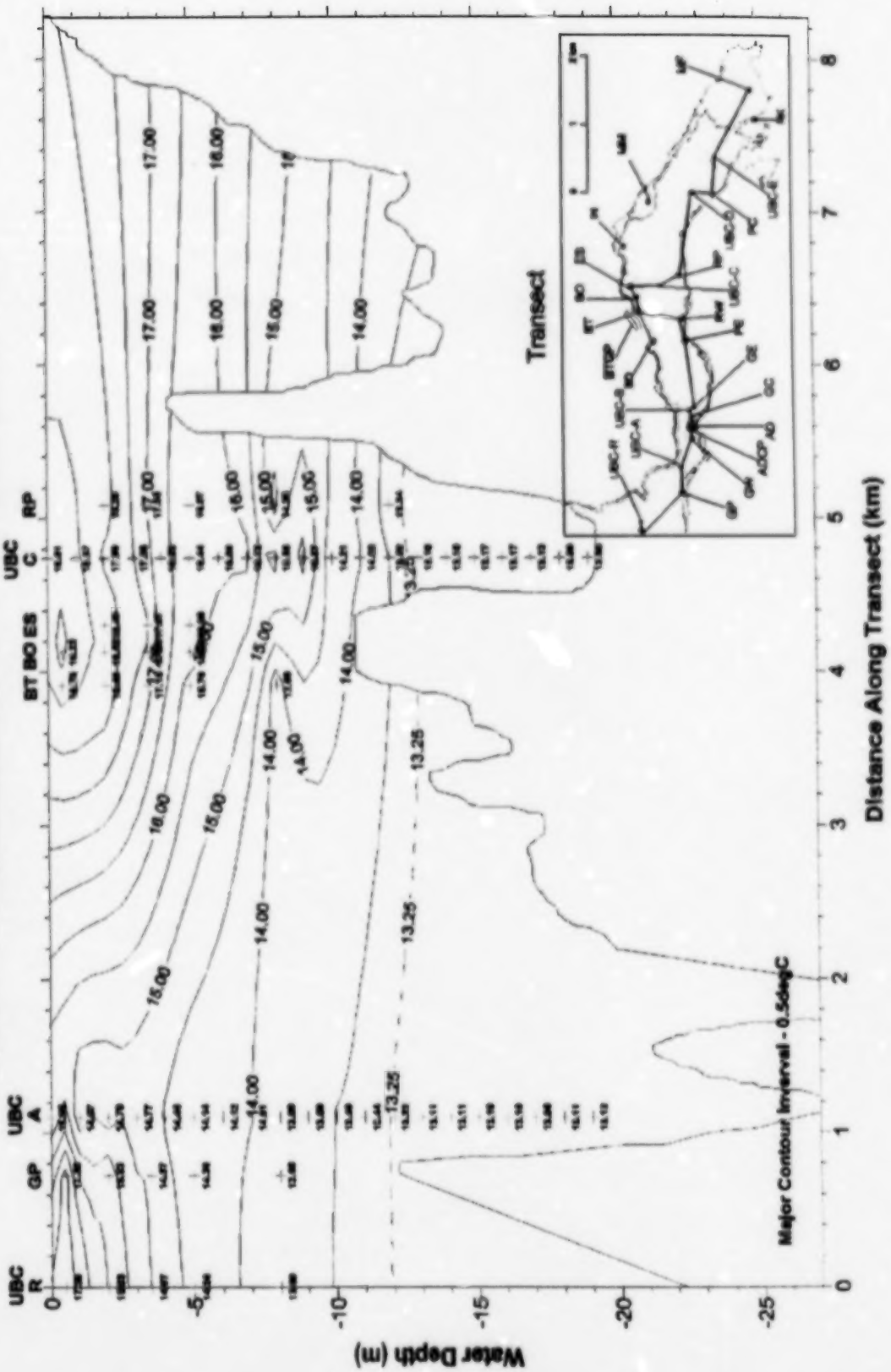
APPENDIX B: LONGITUDINAL TRANSECT, WATER TEMPERATURE-DEPTH CONTOUR PLOTS, PORT MOODY ARM

Monthly mean water temperatures at all available depths and stations have been used to provide a temperature-depth section from the eastern entrance to PMA, past the Burrard Generating Station and further east to the head of the arm, June to September, 1998, and on October 29, 1998 (see location map below). The section was chosen to intercept most of the BC Hydro water temperature stations and also the UBC stations. The data sources are the same as for the contour maps (Appendix A) and are described in Appendix E.2 (Taylor et al. 1999).

Transect: Only stations used in the contouring are indicated along the top edge of the contour plot. Data points are indicated by "+" are values are posted beside each point (°C). Water temperatures are contoured at 0.5 °C intervals, occasionally at 0.25 °C. Note that the relatively sparseness of the available data and tight clustering of some stations has necessitated considerable interpolation and some extrapolation: users should be aware of limitations to accuracy. The contoured sections are followed by tabulations of the data used in preparation of the graphs and brief outline of the strategy used to accommodate as much data as possible. In particular, note that preliminary analysis suggests that temperatures at Station GP track temperatures at UBC-R in Burrard Inlet rather closely, so we have applied the data from one to the other, in those instances when some data are missing.

For further details on preparation of these transects, see Appendix E.2, Taylor et al. 1999.


Port Moody Arm
Water Temperature versus Depth - June 1998
UBC R
GP
BT BO ES
RP
MF
Water Depth (m)
Distance Along Transect (km)
Major Contour Interval - 0.5degC
Transect


Port Moody Arm
Water Temperature versus Depth - July 1998
Water Depth (m)
Distance Along Transect (km)
Major Contour Interval - 0.5degC
Transect
UBC R
GP
UBC A
ST
BO
ES
UBC C
RP
0
-5
-10
-15
-20
-25
1
2
3
4
5
6
7
8
13.25
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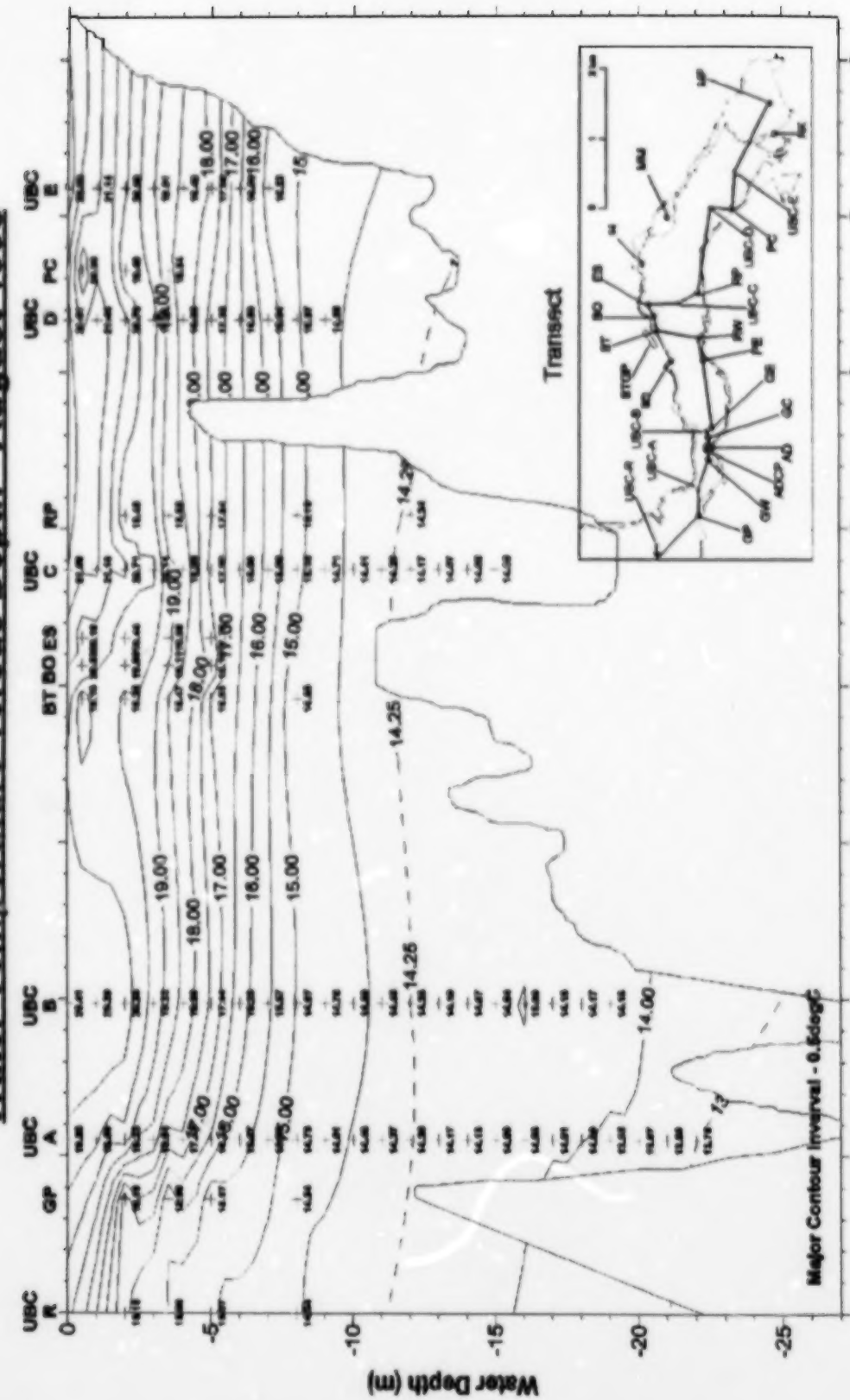
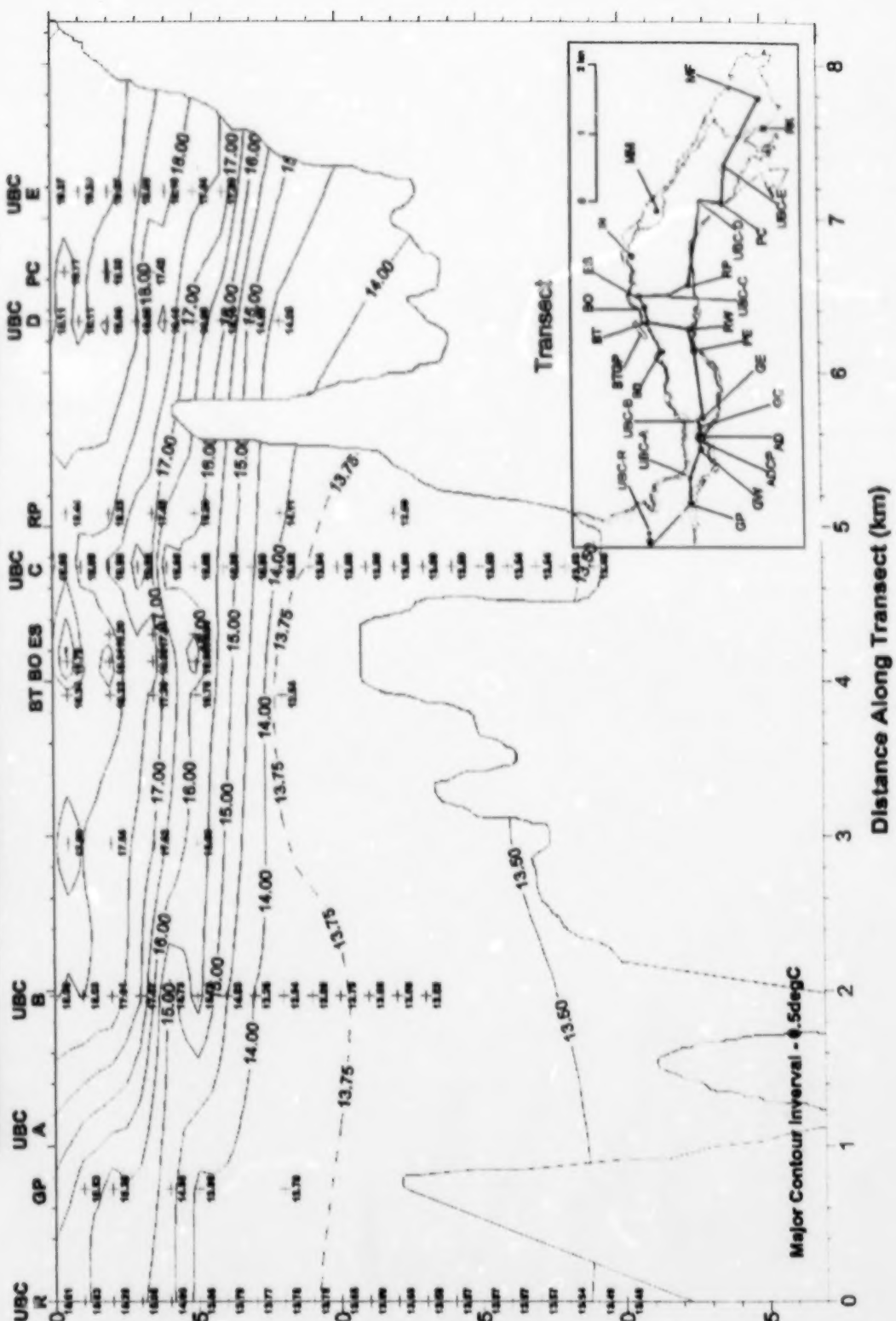
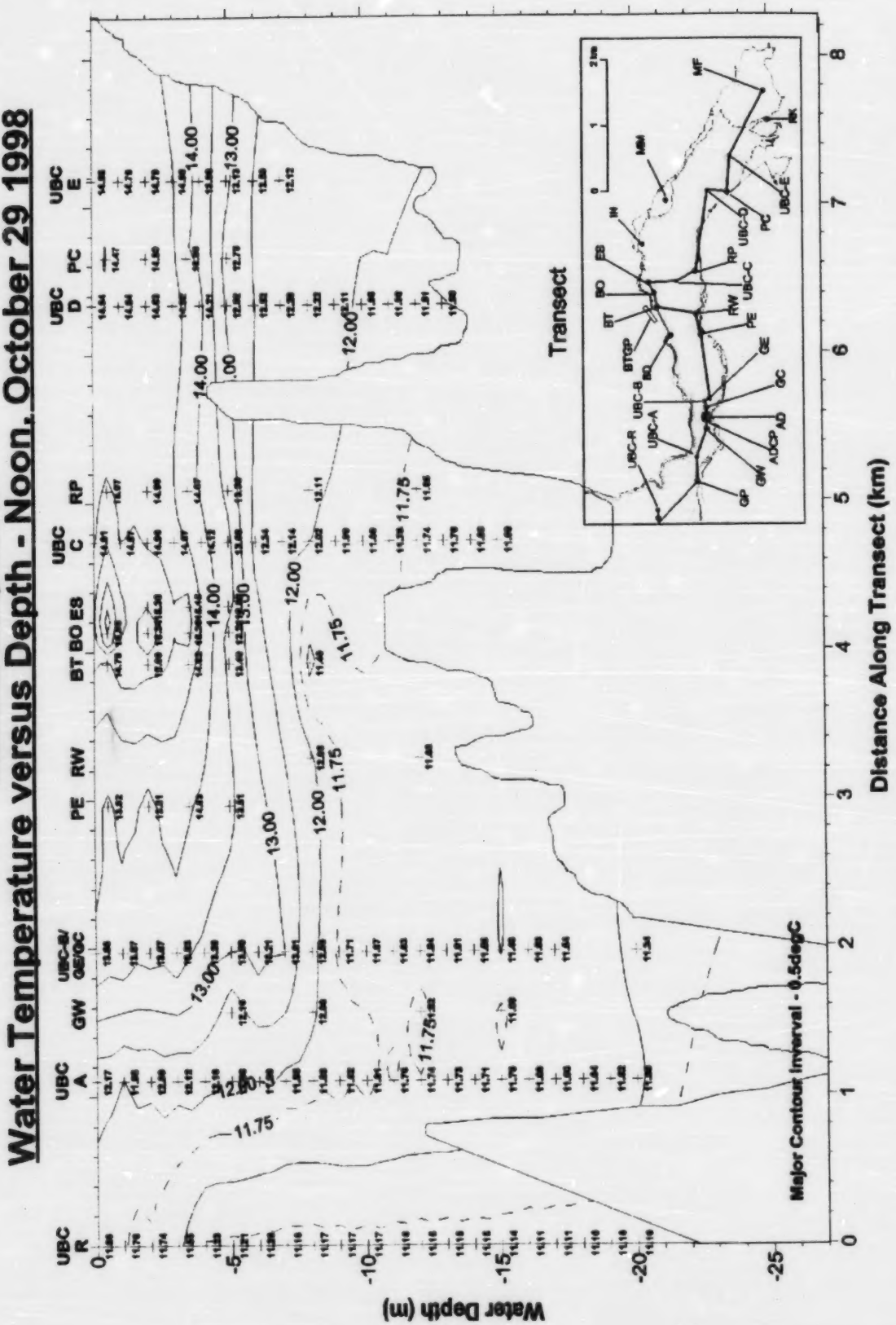
15.00
16.00
17.00
18.00


Port Moody Arm
Water Temperature versus Depth - August 1998
Water Depth (m)
Distance Along Transect (km)
Transect
Major Contour Invarval - 0.5degC
UBC R
GP
UBC A
UBC B
BT BD E3
UBC C
RP
UBC D
PC
UBC E


Port Moody Arm
Water Temperature versus Depth - September 1998
UBC R
GP
UBC A
UBC B
BT BO E3
UBC C
RP
UBC D
PC
UBC E
Water Depth (m)
Distance Along Transect (km)
Major Contour Inverval - 0.5degC
Transect


Port Moody Arm
Water Temperature versus Depth - Noon, October 29 1998
Water Depth (m)
Distance Along Transect (km)
Major Contour Interval - 0.5degC
Transect
UBC R
UBC A
GW
UBC-B/ QE/OC
PE
RW
BT BO ES
UBC C
RP
UBC D
PC
UBC E
11.75
12.00
13.00
14.00

APPENDIX C: SURFACE RADIATION AND ATMOSPHERIC EXCHANGE EQUATIONS

The total heat budget of PMA is described in detail in the report by Fissel et al. (1998). The net surface heating arising from incident solar radiation and heat exchanges with the atmosphere is (Smith and Dobson 1984 p. 8):

$$Q_{net} = Q_S + Q_L - H_S - H_L$$

where

Q_S = absorbed downward short-wave solar radiation

Q_L = net downward long-wave radiation

H_S = upwards sensible heat flux

H_L = upwards latent heat flux

Empirical formulas for each term in the net radiation are available in a number of closely related forms; for this project, we have adopted formulas used by Smith and Dobson (1984), who recalibrated the formulas against measurements made at sea (Fissel et al. 1998).

As in the report by Fissel et al. (1998), where water temperatures are required in the above calculation, we used temperatures at 2 m at Station PC, because of its position almost midway between the Burrard Generating Station and the GVRD weather station at Rocky Point. The 1998 results are presented in Figure C.1. The corresponding results for 1996 - 1997 and a discussion of errors inherent in these calculations are found in Figures 5.8 – 5.13 and Section 5.3.3.3, respectively, in Fissel et al. (1998).

CALCULATION OF HEAT STORAGE IN SEAWATER

The change in water temperature from some convenient base temperature may be used to calculate the cumulative heat storage in the water body over a period of interest. For the calculation in the 1998 report, the arm was divided into 7 segments (Fissel et al., 1998), each segment having one BC Hydro station where water temperatures were recorded. The segment boundaries were adjusted for the 1998 calculation to account for the new Station BO (given a small area from BT) and the decommissioning of Station IN (area split between RP and ES). The vertical segmentation was adjusted for the 1998 calculation to account for the addition of sensors at 3.5 m depth. Details are given in Appendix F.3 in Taylor et al. (1999). Otherwise, the calculation for 1998 was consistent with that for 1996 and 1997.

The net heat gained or lost by one of these elemental water volumes over the period of interest is

$$\Delta Q = C_v.V.\Delta T$$

where ΔQ = Net cumulative heat gained (lost) by water
C_v = volumetric heat capacity (water, 4.187×10^6 J/m^3)
V = elemental volume (thickness of water layer centered at sensor X segment area)
ΔT = temperature change from beginning of period of interest

The heat storage in each segment area of the arm was calculated by summation of the depth elements. The overall water heat storage for the arm was calculated by summing across the segments. Because the segment at the outlet of the arm (around the Gosse Point Station, GP) appears to have different depth, current and mixing characteristics (Waldichuk 1964; Beak 1980; Seaconsult 1995) than the main area to the east, the GP segment was considered separately from the remaining 6 segments (PE and east).

For further details, see Fissel et al. (1998).

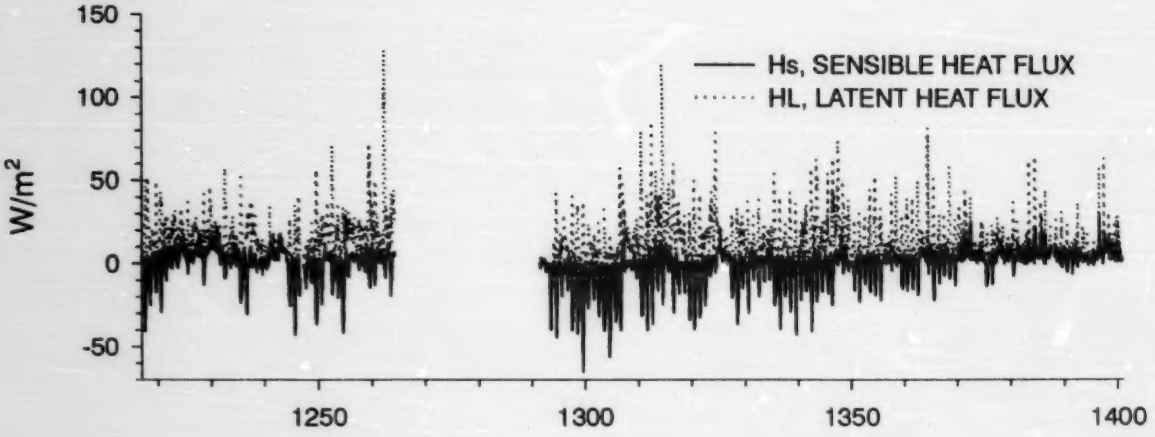


Figure C.1. Port Moody Arm - atmospheric exchanges, station PC.

APPENDIX D: TIDAL HEAT EXCHANGE AND SOURCES OF ERROR

The calculation of the heat exchange at the entrance to PMA (see Tidal Heat Exchange Between Port Moody Arm and Burrard Inlet) is based on a limited measurement program, and several critical assumptions. We discuss here the sources of errors inherent in these measurements and assumptions, and their propagation into the final result. There are two principal types of errors: random errors, which arise from unpredictable variations in experimental conditions, and systematic errors, which give a bias to a measurement.

RANDOM ERRORS

1. *The digital resolution of the temperature sensor* (14%; the manufacturer specifies +/- 0.1°C as the maximum error for the temperature range used in this project (Appendix Z, Fissel et al. 1998). In eq. 3a, temperatures appear as a difference so the maximum error is 0.2 °C, although statistically, it is likely to be less. This is a major consideration, as many of the temperature differences are small (there may also be a systematic error due to calibration - see below).
2. *The current measurements* (2%; +/- 1 cm/s). The instrument gives currents in 2 m depth increments every 10 minutes. The analysis undertaken for this project averages these to hourly values and also to midpoints of the layer structure (Figure 19), in order to coincide with the frequency and depth of the temperature sensors. The instrumental random errors will be negligible after this averaging.
3. *Location errors* (14%) The ADCP (and temperature Station AD) was located by reference to a global positioning system (GPS) receiver, and with reference to shipboard echo soundings during its deployment, the current profiles are accurately located on the chart to about 10 m. Station GC, deployed with the ADCP and anchored to the seabed some 60 m southeast of the profiler, is similarly well located. However, Stations GW and GE were located without advantage of GPS; their separation, estimated at 150 m +/- 15 m is most critical to the gradient calculation.

4. *Calculation of cross-sectional area of channel* (5%) The area was calculated from the limited number of soundings between the two points (Figure 3) by constructing 6 cross-sectional sub-layers as shown in Figure 19.

5. *Physical constants*, density and specific heat of seawater (1% combined, mostly from using nominal values to represent average temperature and salinity conditions in this study).

SYSTEMATIC ERRORS

1. *Offset of the temperature gradient instrumentation from the current profiler* (2%) For the calculation of tidal heat exchange (Summer Heat Budget of Port moody Arm – Update to 1998), the temperature gradient through which the current transports the water is required. In a working harbor, it is not practical to have loggers suspended from floats directly upstream and downstream of the ADCP current profiler. This offset of the

gradient measurements (Stations GW, GE) from the current measurements may be 70 m but is not considered serious (Figure 3).

2. *Representation of channel currents and temperature gradients* (2%) What is important is the positioning of the ADCP and water temperature Stations GW and GE sufficiently clear of shoreline topography and in deep water to take a representative measure of the channel flow and temperature. With the gradient Stations GW and GE, and the ADCP positioned about one-quarter and one-third, respectively, along the channel-section, these stations are well positioned to capture the data required for the heat transport calculation. Major reservations concern the limited depth resolution of the temperature sensors and the uncertain station spacing (see discussion).

3. *Limited temperature resolution with depth* (5%) For the heat transport calculation, current measurements were made every 1 m by the ADCP but it was practical to deploy temperature loggers only at several depths (5, 8, 12 and 15 m). The question of errors in the temperature gradients that may arise from this limited resolution may be gauged by reference to data from the UBC stations (Appendix F.1; Taylor et al. 1999). Figure D.2 shows UBC temperature profiles measured October 29, 1998 at Stations R (west of Gosse Point, Figure 2) and B (mid-channel east of the ADCP deployment, and closest to Station GE; Figure 3). Most of the temperature variability occurs in the upper 8-10 m, which is represented by only two temperature measurement locations..

   For illustration, we compare the temperature differences calculated between UBC Stations B and R, first using the full data set for October 29 and taking the average gradient over each layer, and then using only the single point data at 5 m, 8 m, 12 m and 15 m (Figure D.3). In layer 1, the measurements at 5 m yield a temperature about 0.1°C (5%) lower than the average of the 7 measurements across the layer; in layer 2, the 8 m measurement is about 0.25°C (2.5%) too high; and the mid-point data and the averages agree within a couple of 0.01°C in layers 3 and 4. For the temperature gradient, the temperature difference is divided by the station separation (units °C/km). While Station UBC-R is west of Gosse Point in Burrard Inlet, its temperatures closely track those at Gosse Point (see comments in Appendices A and B) and may be considered representative of mid-channel temperatures off Gosse Point. If so, the temperature gradient between UBC-B and a position off Gosse Point appears similar in magnitude to the gradient between GE (near UBC-B) and GW, which have some 150 m separation.

   Stations UBC-B, GE, GW and AD lie within 200-300 m of one another. Water temperatures at the 20 m sensors at GW and GE and the 27 m AD sensor suggest that a linear, isothermal extraction to the seabed is warranted (Figure D.1, D.2).

4. Offset in temperature calibration (20%) One logger may have a bias relative to the second logger of 0.1 °C, due to the interchangeability specification by the manufacturer (see Appendix Z, Fissel et al. 1998).

Table D.1 Summary of random errors and their impact on the magnitude of tidal heat transport

Parameter	Possible error in parameter	Impact on magnitude of tidal heat transport calculation	Comments
Velocity, mean over layers	2%	4%	Enhanced impact because velocity appears twice in eq. 3a
Temperature difference	+/- 0.1°C	14%	
Station separation	14%	14%	
Channel cross-sectional area	5%	5%	
Constants	2%	2%	
Overall estimate =		21%	

Table D.2 Summary of systematic errors and their impact on the magnitude of tidal heat transport

Uncertainty	Possible impact on tidal heat transport calculation	Comments
Offset of temperature from current measurements	2%	
Measurements representative of entire channel	2%	
Limited temperature resolution with depth	5%	Mostly effects upper 10 m where temperature variability is greatest
Offset in calibration between two temperature loggers	20%	
Overall estimate =	21%	

Overall (random and systematic errors) = 30%